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TOTAL SEDIMENT LOAD MEASURED IN TURBULENCE FLUME

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CONTENTS

ILLUSTRATIONS

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ILLUSTRATIONS

Synopsis

The results of significant model and prototype tests of a turbulence flume are presented in this paper. The model tests were made in a glass-walled flume. Velocity of flow and the ability of the flume to transport the total sediment load in suspension were observed under varying conditions of flow and resistance to flow that resulted from vertical baffles, which were fastened to the floor of the flume. The prototype tests consisted of observations of velocity and sediment concentration for all flows at the measuring sill and for normal flows upstream and downstream from the flume. Samples of total sediment load and bed material were analyzed for particle size. Minor studies of dune movement in model and prototype are also included.

Pertinent observations during the investigation are as follows:

Model tests

1. With the proper baffle arrangement, the total sediment load could be transported in suspension over the measuring sill for concentrations up to 2,000 ppm and for stream discharges of 250 to 800 cfs.

2. At a discharge of 400 cfs, the optimum baffle arrangement resulted in a water-surface fall of 0.53 ft through the flume.

Prototype tests

1. The total sediment load was transported in suspension at the measuring sill for concentrations from 539 to 3,150 ppm and water discharge from 160 to 570 cfs except for intermittent deposition of sediment in the flume and on the measuring sill adjacent to the left bank. This deposition resulted from brush growth on the left bank upstream and downstream from the flume and from the change in the dirction of the thread of flow downstream from the flume.

2. The fall in the water surface through the flume ranged from 0.18 to 0.48 ft.

3. The intermittent deposition of sediment in the flume and on the measuring sill adjacent to the left bank was eliminated by raising the height of the first two rows of baffles 0.5 ft. The change in the height of the baffles increased the fall through the flume to a maximum of 0.54 ft.

Introduction

The proper development of river control structures, particularly those constructed in alluvial channels, requires data on the total sediment discharge of streams. The suspended load for most streams can now be easily determined with standard sampling equipment, except where the debris load prevents the water-sediment mixture from entering the intake nozzle at stream velocity. The bed load, or remainder of the total load, cannot be measured satisfactorily with available sampling equipment. The concentration and particle-size distribution in the vertical section from point-integrated suspended-sediment samples are significant to bed-load movement, but the rate of movement cannot be determined with assurance from this qualitative information. The deficiency of information on rates of bed-load movement in natural streams became acute in 1948 in connection with the sedimentation investigations in the Loup River basin, Nebr. As a result, the U. S. Geological Survey undertook the design and development of a new apparatus, a turbulence flume, for the measurement of total sediment load in the Middle Loup River at Dunning, Nebr. The investigation has been made in cooperation with the U. S. Bureau of Reclamation.

The hydraulic design and laboratory model studies were conducted by the Civil Engineering Department through the Research Foundation of Colorado Agricultural and Mechanical College, Fort Collins, Colo. Preliminary plans were sent to the Geological Survey in June 1948, and a final report was issued in July 1948.(1)[4] The structural design and the construction plans and specifications of the prototype were prepared by the Geological Survey. Construction of the flume was begun in October 1948 because the need for information on total sediment discharge was urgent. The flume was completed in May 1949, and the recording gage installation was completed in August of the same year. The collection of basic data started on June 4, 1949.

A convenient site for the flume was found in a reach of the Middle Loup River at Dunning, and it was considered satisfactory for the following reasons:

4 Numerals in parentheses, thus: (1), refer to corresponding numbers in the Bibliography; see Appendix.

1. The flume site was downstream from a proposed reservoir and upstream from a proposed diversion structure. (See fig. 1.)

2. The stream characteristics were considered rather typical of the sand-hill area. (See fig. 2.)

3. The stream flow was uniform and had no sharp peaks from precipitation or snow melt.

4. The stream was flowing on a sand bed of considerable depth.

5. The sediment in transport consisted largely of medium to fine sand.

6. The information to be obtained could be used as a basis for studies of the total sediment load at other sediment measuring stations in the Loup River basin and in other areas where similar conditions exist.

The density of stream channels in the sand-hill area of Nebraska is very low because the infiltration rate is high. The drainage area of the Middle Loup River at Dunning is 1,760 square miles; only about 80 square miles contribute directly to surface runoff. The stream flow comes from ground water sources and is very uniform except during periods of high precipitation, which causes some surface runoff. The maximum daily water discharge during the period of record (1945-50) was 821 cfs; the minimum, 220 cfs. The stage-discharge relationship is very unstable, as the stream bed is composed of erodible material. A typical particle-size distribution of bed material is given in figure 3.

The Department of Roads and Irrigation, State of Nebraska, granted permission to install the turbulence flume at the highway bridge on the Middle Loup River at Dunning, Nebr. This specific location was chosen to minimize operation and construction costs.

Design and Model Studies

The most comprehensive laboratory studies of bed-load movement were described by Gilbert (2) in a paper published in 1914. Since that time, investigations by O'Brien (3), Straub (4), Kramer (5), Einstein (6), Vogel (7), and European investigations (8, 9, 10) have added much information to this perplexing problem of bed-load movement. These investigations, although limited to studies of the fundamental laws governing bed-load movement, were of material assistance in developing an apparatus whereby the bed load could be temporarily transported in suspension and measured as suspended load. The specific studies by Johnson (11) and Powell (12), field investigations by the Geological Survey (13) in the Boise River basin, Idaho, and the cooperative study conducted at the University of Iowa and University of Minnesota (14) added additional information significant to the problem.

Analysis of the Problem

As pointed out in the introduction, a method was needed for measuring the bed load, or that part of the total load not measured by standard suspended-sediment samplers, such as the US D-43 or the US DH-48 (14). Any method developed should be readily adaptable for use on the Middle Loup River with a minimum of effort and time expended in actually making measurements and a minimum of expense involved in the initial construction. Two methods of solution to the problem were:

1. To trap the bed load (unmeasured load) that passed a given point during a measured period of time.

2. To force the bed load (unmeasured load) into suspension by increased

turbulence so that the bed load could be measured with standard suspended-load sampling equipment.

Any equipment for trapping bed load would have to be operated continuously in order to obtain a representative sample when equilibrium is reached. If the equipment were not operated continuously, the regime in the river would be changed when operation did begin and the operating time required to re-establish equilibrium could be too great to permit practicable operation.

Because many tons of bed material pass a given section in the river each day, the size of equipment for continuous trapping would rule out this method of solution to the problem; the excessive time and expenditures of money required for construction and operation would be prohibitive. Furthermore, there would be no assurance that the material being trapped included all, and only, the unmeasured load.

Two possible methods of forcing the bed load into suspension by increased turbulence are:

1. Turbulence created by energy from some external source, such as mixing devices or jets of air or water.
2. Turbulence originating from the energy of the river itself, as the installation of baffles to increase the turbulent energy of the flow at the expense of the potential energy of the stream.

The latter method, that of utilizing a part of the energy of the stream to create the turbulence necessary for bed-load suspension, was adopted as the more practical. This method permits continuous operation of the system so that measurements of total load can be made at any desired time.

From the work of Johnson (11) and Powell (12), it was evident that baffles could be used to cause large energy losses in a stream. Therefore, preliminary tests were made with continuous baffles across the floor of the model. These tests disclosed, however, that the bed-load material, which moves downstream in the form of dunes, increased the elevation of the stream bed and completely covered each baffle as the dunes progressed downstream. In view of this situation, it was decided to use a system of individual baffles so that the remainder of each dune could move between adjacent baffles until sufficient turbulence had been created by flow past subsequent baffles to force all the material into suspension. Because of the need for creating the maximum amount of turbulent energy, baffle plates (fig. 5) were chosen rather than rectangular battens as used by Powell. Furthermore, the separation zone, or wake, downstream from each baffle plate was more stable and less dependent on Reynolds number--a matter of prime importance in model studies that involve free surface flow.

In order to simplify and systematize the research for this problem, a dimensional analysis was made. The initial objective was to determine that arrangement of baffles which would create the maximum turbulence through the structure--hereafter called the turbulence flume. The head loss ΔH, which is dissipated as turbulence, is dependent (fig. 4) on the size and arrangement of the baffles, the characteristics of the flow and sediment, and the properties of the water. This may be expressed in general functional form as

$$\Delta H = \phi, (h, b, x, s, v, d, c, \omega, \sigma s, \rho_s, \rho, \mu, \Delta\gamma) \tag{1}$$

where

ΔH is the drop in water-surface elevation through the flume or through the roughness section used for the special loss studies.

h is the height of the baffles.

s is the longitudinal spacing between the rows of baffles.
x is the open distance laterally between adjacent baffles in a row.
b is the width of a baffle.
v is the mean velocity of the water in an undisturbed section of the stream.
d is the mean depth of tthe water in an undisturbed section of the stream.
c is the concentration of sediment being transported by the stream.
ω is the mean terminal fall velocity or settling velocity of the sediment in the stream.
σ_S is the standard deviation of the fall velocity of the sediment--a measure of the size gradation.
ρ_S is the density of the sediment.
ρ is the density of the water.
μ is the dynamic viscosity of the water.
$\Delta\gamma$ is the difference between the specific weights of the water and air.

which may be stated dimensionlessly as

$$\frac{\Delta H}{h} = \phi_2 \; \frac{b}{h}, \frac{x}{h}, \frac{s}{h}, \frac{d}{h}, c, Fr, Re, \frac{\omega}{v}, \frac{\sigma_S}{\omega}, \frac{\rho_S}{\rho} \tag{2}$$

where
Fr is the Froude number.
Re is the Reynolds number.

A complete investigation of equation 2 was obviously impossible in the time available, so various parameters were either held constant or eliminated as being of secondary importance. By assuming that the baffle arrangement which would give maximum head loss for flow without sediment would be the same as that with sediment, the sediment was not used during the roughness tests. Because the turbulence was great and all separation zones stable, the Reynolds number was considered to be of little importance. By maintaining the Froude number and relative depth, d/h, constant from model to prototype, equation 2 becomes

$$\frac{\Delta H}{h} = \phi_3 \left(\frac{b}{h}, \frac{x}{h}, \frac{s}{h}\right) \tag{3}$$

Equation 3 is sufficiently simple to be studied systematically.

In order to determine whether baffles had the same characteristics as the battens used by Powell (12), a test was made with continuous baffles. The results in figure 4 show that the loss is minimum at a value s/h =10, which is nearly the same as that found by Powell. The individual baffles required adequate lateral spacing to permit the passage of dunes. To meet this requirement, a density factor of x/b = 2 was assumed as that most desirable. With this arrangement, the maximum head loss over the 6-ft length of test section was found to be at s/h = 2, as shown in figure 4. The arrangement of baffles, measuring sill, and end sill in the preliminary model tests are shown in figure 5.

On the basis of the foregoing analysis and other preliminary tests, it was decided to use a density factor of x/b = 2. A prototype baffle height, h, of 6 in. was selected as the initial size for model investigations with sediment. If the maximum loss were to be obtained with this height, it would be necessary to space the rows of baffles 1 ft apart longitudinally. Because this spacing required such a large number of baffles, a spacing of 2 ft was chosen

for the preliminary value of s. The flow characteristics for maximum head loss were assumed to be the most desirable for the suspension of total load, because the energy dissipated is first converted into turbulent energy and then into heat. A further assumption was made that the flow characteristics for maximum turbulence are also those that will suspend the greatest amount of sediment.

A concentration of 2,000 ppm was established as the maximum that the turbulence flume must force into suspension. Therefore, equation 2 was reconsidered with the sediment parameters included. For this equation, however, the concentration is considered a maximum that can be carried for a given set of flow conditions, and the baffle height thereby becomes the dependent variable in a separate equation. By holding the relative depth, the relative baffle height and arrangement, the concentration, the Froude number, the relative fall velocity, the standard deviation, and the density ratio constant from model to prototype, the model action would give a true representation of the prototype action. Although such limitations are possible theoretically, they are sometimes difficult practically, as will be discussed in the following paragraphs.

Design and Construction of Model

The purpose of this model study was twofold:

1. To determine the size and arrangement of baffles necessary to force the bed load into suspension.
2. To determine the head loss through the structure that would result from an economical system of baffles.

In order to accomplish these objectives, a flume was built that had a test section 2 ft wide and 13 ft long. Upstream from this section was a section 4 ft wide and 10 ft long with a transition between the sections. This arrangement permitted a boundary layer to develop relatively unmodified along the floor of the flume while the boundary layer along the walls was contracted at the transition and thereby reduced in effectiveness--a measure taken in order to produce flow that was as nearly two-dimensional as possible.

A model scale of 1:4 was selected after preliminary tests disclosed that a 1:8 ratio was unsatisfactory. The 2-ft test section then represented a prototype width of 8 ft, which was approximately a quarter of the span between piers of the Dunning bridge. The 6-in. high baffles required model baffles 1-1/2 in. high. These baffles were made of No. 20 gage galvanized sheet metal and had a 1/2-in. flange at the base so that each baffle could be secured in place with thumb tacks. The base of the model was made of exterior plywood, and the measuring sill and end sill were made of white pine.

The discharge in the model was fixed by the Froude criterion and by the limits of 250 cfs and 800 cfs for which a concentration of 2,000 ppm must be transported in suspension across the measuring sill. Therefore, tests were run at model discharges that simulated 250, 400, and 800 cfs. An attempt was made to obtain sand of the proper size to have the velocity ratio, w/v, the same in the model as in the prototype. The small size of sediment required for the model made it difficult to find material with the proper fall velocity. The following table gives the velocity ratio for both the prototype and the model:

Ratio w/v of the mean fall velocity of the sediment to the velocity of flow in the river

Discharge	Prototype	Model
200	0.098	0.160
400	.072	.120
800	.051	.084

Although it was not possible to obtain sufficient quantities of sand small enough to make the w/v ratio a constant, the deviation is in the direction of safety. If it is possible to force into suspension sand of a given fall velocity, it should be possible to force into suspension the same concentration of a smaller sand that has a lower fall veloctiy.

The sand used in the model studies was obtained near Fort Collins. It was passed through a 30-mesh screen and then washed. The size analysis before and after washing is shown in figure 6.

Preliminary tests demonstrated that it would not be possible to obtain a sufficiently high velocity through the structure without constricting the flow by raising the floor above the bed of the stream. In fact, it was found necessary to approach critical velocity over the measuring sill for all discharges.

Operation of Model

The preliminary experiments demonstrated that if continuous baffles were used, the advancing sand dunes would cover each baffle in turn as the dunes progressed downstream. Individual baffle plates 0.5 ft high and 2 ft long were then tested, and it was found that only for a rather low concentration of sediment was it possible to prevent the advancing dunes from first covering the baffles and eventually the measuring sill. Therefore, all the final experiments were run with the baffles at least 1.0 ft high.

After considerable difficulty, a sand-feed mechanism was devised that would feed the sand into the model at a continuous rate. It was composed of a reciprocating plate that moved at the base of a hopper. A vibrator was mounted on the side of the hopper to keep the sand in a "fluid" state, which permitted the sand to flow freely. The relative position of the model and the sand-feed mechanism is shown in figure 7. The sand was introduced a sufficient distance upstream to insure adequate time of fall for the particles to reach the bed of the stream 10 to 20 ft (prototype scale) upstream from the first row of baffles.

Each test was run until equilibrium had been established and a proper evaluation of the capacity of the design could be made. This procedure sometimes took several hours, although generally the time required was less than an hour.

A point gage mounted on a carriage, which bridged the channel, was used to determine the water surface profile and the head loss through the flume. The sand was trapped in a 4- by 8-ft weir box at the end of the flume.

Photographs were taken both before and after each test to show the flow pattern of the water and the patterns of the dunes and deposists of sand.

Results of the Model Tests

The data from the model studies were obtained by measuring or observing the following items:

1. Head loss through the flume.

2. Flow pattern past the baffles and across the measuring sill.
3. Dune pattern upstream from and in the flume.
4. Dunes, deposits, and bed load moving over and near the measuring sill.
5. Action immediately downstream from the end sill in regard both to water and to sand movement.

When the baffles were only 0.5 ft high, the sand could not be forced into suspension but instead covered each of the baffles as it progressed downstream. This is shown in figure 8, where none of the baffles can be seen either during or after operation. For a discharge of 250 cfs the measuring sill was about half covered with a sand dune, and the tops of several baffle plates were exposed. For 400 cfs, however, the measuring sill was completely covered, and only one or two baffles could be located. When a discharge of 800 cfs was flowing through the flume, the sand bed was nearly smooth, and there was no visible evidence of either the measuring sill or the baffle plates. The head losses through the flume for the three discharges were 0.73, 0.19, and 0.21 ft, respectively.

Because this operation of the 0.5-ft baffles was unsatisfactory, the height of the baffles was increased to 1.0 ft; the location and arrangement remained the same. As may be seen in figure 9, the measuring sill remained uncovered regardless of the discharge. Deposits were found immediately downstream from each baffle. Furthermore, the upstream baffles were periodically covered almost completely. This was a result of dunes advancing on the baffles and, as the dune proceeded downstream, the baffle would again be uncovered at least partially. The head losses were 0.82, 0.48, and 0.33 ft for 250, 400, and 800 cfs, respectively. The water surface, having waves 0.5 ft high, was irregular for a discharge of 250 cfs; but as the discharge, and hence the depth, was increased to 800 cfs, the water surface became rather smooth.

The 1-ft baffles created sufficient turbulence to transport the entire concentration of 2,000 ppm in suspension over the end sill regardless of the discharge. However, the margin of safety was narrow enough, in considering the unprecedented nature of such a model-prototype experiment, that tests were also made with the two upstream rows of baffles 1.5 ft high and the remainder 1.0 ft high. Figure 10 shows clearly that, although a small deposit remains downstream from each baffle, the measuring sill is clear and there is no tendency for any of the baffles to become completely covered with the advancing dunes. The irregularities of the water surface were somewhat increased, and the head losses were 0.86, 0.53, and 0.42 ft for discharges of 250, 400, and 800 cfs, respectively.

The end sill operated satisfactorily for all flows, which had no tendency to undermine the structure.

In conclusion it could be said that both the 1.0-ft and 1.5-ft baffles satisfactorily forced the bed load into suspension. However, the 1.5-ft baffles accomplished this purpose with a greater margin of safety but with a greater amount of surface disturbance and a slightly increased head loss.

The concentration of suspended sediment that passed over the measuring sill was determined by sampling with a nozzle made of 3/16-in. i.d. brass tubing. A syphon tube was attached to the nozzle and arranged so that the velocity of flow within the tube was the same as that outside the tube. By this means, point-integrated samples were obtained at nine depths in the vertical at the center line of the flume. Samples were also taken at the quarter points, as shown in figure 11. The mean concentration was 710 ppm in the center vertical and 690 and 720 ppm at the right and left quarter points, respectively.

As would be expected, the distribution of sediment shows a smaller concentration near the water surface than near the sill. The average concentration of the total load in the model was 710 ppm for a discharge equivalent to 360 cfs in the prototype.

The sand dunes were measured as they approached the model. Although the dunes were irregular in size and shape, an attempt was made to determine the average size and velocity of movement of the dunes by photographing the dunes at the glass wall at 5-min intervals. This system of measurement, of course, included an error that was due to the effect of the glass wall but was the only system that was readily adaptable. Visual observation indicated that the error was not significant.

From 70 measurements the average velocity of movement of the dunes in the model was found to be 4.5 ft per hr with a standard deviation of 2.2 ft per hr. The height of the dunes varied considerably, but the average was approximately 0.12 ft. By using the average height and velocity of the dunes, the measurements indicated that the concentration of material moving as dunes was approximately 160 ppm.

Measurements of the concentration of suspended sediment were taken upstream from the model structure by depth integration. The average concentration was 430 ppm. If the total load at the sill is taken as 710 ppm and the suspended load upstream as 430 ppm, apparently 280 ppm moves as bed load or unmeasured load. Based on the measurements of the dunes, 160 ppm of the 280 ppm was moving as dunes and 120 ppm was moving as unmeasured suspended or saltation load and bed load not reflected in the dunes.

Samples were collected from the surface of the stream bed with a withdrawal pipette. The amount of air pressure used was sufficient to withdraw the sediment sample without disturbing the surface of the bed. The mean size of samples collected in this manner was 0.359 mm. The mean size of sediment in the bed of the model was 0.305 mm. when tests were started.

Recommended Design of Prototype Structure

In view of the foregoing tests and observations, it was recommended that:

1. The prototype be constructed with nine rows of removable baffle plates 1.0 ft high and 2 ft wide with a lateral spacing of 6 ft and a longitudinal spacing of 2 ft from center to center.
2. A continuous baffle 0.5 ft high be placed 24 in. downstream from the last row of baffles and 28 in. upstream from the 6- by 16-in. measuring sill.
3. The end sill be placed 56 in. downstream from the measuring sill.
4. Sheet piling be used both upstream and downstream to reduce the hazards of piping and possible failure of the structure.

The baffle plates were designed sufficiently long to withstand reasonable impacts from floating debris and yet short enough to prevent gross nonuniformities in sediment discharge over the end sill. The purpose of the end sill was to help to obtain a more uniform lateral distribution of sediment. When the ratio $s/h = 2$ (fig. 4), the maximum head loss is produced for a density ratio $x/b = 2$. The arrangement of the roughness baffles can be altered should additional data indicate that a different spacing would be more efficient.

The Prototype Flume

The turbulence flume is a structure for inducing turbulence sufficient to suspend substantially the total sediment load of a stream. It consists of a

series of 1- by 2-ft movable baffles, one continuous 6-in. permanent baffle, and a 6- by 16-in. wooden baffle (measuring sill) attached to a reinforced concrete slab 82 ft wide and 38 ft long. The 1- by 2-ft baffles are galvanized steel sheets supported by two round rods inserted in pipe sockets embedded in the concrete slab. The permanent baffle, a 6- by 4-in. angle, and the wooden measuring sill are bolted to the concrete slab.

The concrete slab, which is the floor of the flume, is supported at each end by interlocking sheet steel piling driven to a depth of 10 ft. The top of the slab is just below the average elevation of the stream bed for a discharge of approximately 400 cfs. The wooden end sill, which is bolted to the downstream end of the slab, was designed to produce a reverse roller to prevent scour of the stream bed immediately downstream from the flume.

A gage well and recorder shelter are located on the left bank 25 ft upstream from the flume. The well is equipped with two 3-in. intake pipes with static tubes to eliminate draw-down. A continuous record of the elevation of the water surface is obtained with an automatic water-stage recorder. The elevation of the water surface at the downstream end of the flume is obtained from a staff gage attached to the downstream wing wall of the right bridge abutment. Walkways were installed just below the upstream edge of the slab and just downstream from the measuring sill to simplify the collection of depth-integrated sediment samples. Figure 12 shows a skeleton model of the prototype flume with the bridge deck removed. Details of the prototype flume and baffle arrangement are given in figures 13, 14, 15, and 16.

Operation of Prototype Flume

The initial investigations of the efficiency of the flume consisted of concurrent determinations of water surface slope, stream velocity, suspended-sediment concentration, and size of sediment in transport.

Sampling Procedure and Analysis

The quantity and distribution of the sediment were obtained from samples collected biweekly with the US DH-48 and US P-46 samplers at representative points in the cross section at the measuring sill. Several sets of instantaneous samples were also collected with the Tait-Binckley sampler.

The position of the US DH-48 sampler when in transit was controlled by means of a guide arrangement so that the nozzle remained horizontal and so that the sampler nozzle would come to rest momentarily on the measuring sill when the direction of transit was reversed. This method insured uniformity of procedure in the collection of samples. Point-integrated samples were collected in the usual manner except that the bottom sample was obtained with the sampler nozzle resting on the downstream edge of the measuring sill. Instantaneous samples were collected with the upper end of the Tait-Binckley sampler resting on the sill.

The operation of the prototype flume at a discharge of 350 cfs is shown in figure 17. (Guide arrangement for collection of samples with a US DH-48 sampler is not shown.)

Standard laboratory procedures were used in the analysis of the sediment samples. Suspended-sediment concentrations were obtained by the Gooch crucible method. Particle-size distributions were determined with the bottom-withdrawal tube and by dry sieving. The sieve openings were checked by microscopic methods.

Measurements of Velocity and Fall in Water Surface

The velocity measurements were made with the Price current meter in accordance with the standard field practices of the Geological Survey. The fall through the flume was determined from staff gages located on the right bank at the upstream and downstream ends of the flume. The staff gages are direct reading, and they are marked at intervals of 0.02 ft.

Flume Operation

The flume as originally construced was in operation during the period June 1949 to March 29, 1951. During this interval deposition in the left end of the flume and on the left end of the measuring sill was intermittent. Downstream from the bridge the stream channel has a 10-degree bend to the right. This change in direction and the presence of brush growth on the left bank, particularly just downstream from the flume, reduced the velocity in the left end of the flume. Sediment was also deposited downstream from each bridge piling. In the original design, it was planned to enclose the bridge piling that comprises each pier, but this was not done because later observations indicated that the effect of the piers on the distribution at the measuring sill was negligible.

The flume operation during the test period was considered satisfactory except for the intermittent deposition of sand on the measuring sill. This deposition indicated that the turbulent energy was insufficient to suspend the total sediment load during maximum dune movement through the flume. On the basis of the results of the model studies, the first two rows of baffles at the upstream end of the flume were raised 0.5 ft. (See fig. 15.) This change was made on March 29, 1951. Since that date, the flume and measuring sill have remained clean except when debris becomes lodged in the flume and when there is backwater from ice during winter periods.

Vertical Distributions of Velocity, Concentration, and Size of Sediment

The turbulence created in passing each successive baffle plate should progressively suspend greater amounts of the total quantity of sediment that is passing through the flume until the turbulence created by flow in passing the last baffle (1 by 2 ft) is sufficient to suspend the remainder of the total quantity of sediment. When all the sediment is in suspension, the capacity of the flow to transport sediment in suspension must at least be equal to the quantity of sediment available for transport. With its capacity at least equal to the concentration of the total sediment load, the flow should suspend its load of sediment throughout its depth with respect to both concentration and size of the suspended sediment.

Typical vertical distributions of velocity, concentration, and size of total sediment load are shown in figures 18 and 19. The curves indicate that the turbulence is sufficiently great to suspend at the surface the coarsest fraction of the load in transport. The vertical size-distribution curves of figures 18 and 19 show the percentages of material coarser than 0.25 mm (material that is not found in appreciable quantities at normal sections upstream from the flume) that was sampled at the several elevations above the measuring sill. If the material coarser than 0.25 mm (coarse sand) was uniformly distributed throughout the depth, then the total sediment load should be in suspension; therefore, the percentage coarser than 0.25 mm was selected as the reference

size. Normally, the vertical distributions of concentration and size of total sediment load would show an appreciable decrease of both size and concentration with distance above the bed of an alluvial stream.

The turbulence flume has a measuring sill that will allow a standard sediment sampler to integrate the concentration of the total sediment load (now in suspension) throughout the entire depth of flow. Samples thus obtained are samples of the total sediment load, provided the bed load moves at stream velocity and does not form deposits on the measuring sill.

In figure 18, all baffles are 1.0 ft high, and the vertical distributions for stations 10, 25, and 70 show that both concentration and size of suspended sediment are relatively uniform with respect to depth. This indicates that the turbulence at these stations is sufficiently great to suspend the coarser fractions throughout the depth of flow. Stations 40 and 55 (fig. 18) show an appreciable increase in concentration with depth and a noticeable increase in size of suspended sediment with depth. This pattern indicates that turbulent mixing has not developed at stations 40 and 55 to the extent in which it has at other stations or that the concentration of sediment is so great that it nears the capacity of the flume.

The vertical distribution curves of figure 19 indicate a higher degree of turbulent mixing for the entire cross section than do the curves of figure 18. All flow characteristics were the same for the two sets of curves, except that the baffles in the two upstream rows were higher in figure 19. Figure 18 represents transport before, and figure 19 represents transport after, the height of the upstream baffles was increased. As shown in figures 8 and 9, the capacity of the flume to suspend the sediment bed load was increased when the first two rows of baffles were raised to a height of 1.5 ft. A comparison of the curves of figures 18 and 19 shows that a change in the distribution curves has taken place. Although the distribution curves are more irregular with the higher baffles, they are also more uniform, which indicates increased turbulence. As would be expected, station 70 was changed considerably, but station 10 was changed very little. The zone around station 50 was carrying the heaviest load for both arrangements of baffles.

Figure 20 shows the vertical distributions of concentration and size of suspended sediment as obtained by an instantaneous Tait-Binckley sampler. These data supplement those obtained with the US P-46 sampler.

Lateral Distributions of Velocity, Concentration, and Size of Sediment

From figure 13 it can be seen that the baffle arrangement is such that if a quantity of sediment were released at the center of one of the most upstream baffles, the water-sediment mixture resulting should theoretically be distributed over a 49-ft width at the measuring sill. Actually, the turbulence created in passing through the flume appears to carry suspended sediment past the measuring sill in large-scale eddies of high concentration. Figures 21 and 22 are illustrations of this fluctuation of suspended-sediment concentration with time. These measurements were taken on June 27, 1951, after the height of the two upstream rows of baffles was increased. The data shown are for depth-integrated samples collected at 5-min intervals over a 4-hr period at the four daily sampling verticals above the measuring sill of the flume. A statistical analysis of the data indicates that a single sample collected at any one vertical at any given time might vary nearly 83.5 percent (see station 30) from the true mean for the vertical. The standard deviation of the variations at station 30 is 267 ppm which, if for study the normal error

distribution is assumed, means that the variation will be less than ± 83.5 percent for 99.94 percent of the time. The normal error distribution also indicates that the variation will be less than ± 73.1 percent for 99.7 percent of the time, less than ± 48.8 percent for 95.5 percent of the time, and less than ± 24.4 percent for 68.3 percent of the time. Such a variation is the greatest computed and occurs about the mean of station 30 only. For station 10, the variation about the mean will be less than ± 23.8 percent for 95.5 percent of the time; for station 50, it will be less than ± 22.0 percent for 95.5 percent of the time; and for station 70, it will be less than ± 29.2 percent for 95.5 percent of the time.

The variation of the mean concentration for the cross section (stations 10, 30, 50, and 70) during the 4-hr period is less than ± 24.8 percent for 95.5 percent of the time. In order to determine the increased accuracy resulting from two sets of samples, the average concentrations for successive 5-min intervals were computed and analyzed. By this means the accuracy may be increased so that the variation will be within ± 18.6 percent for 95.5 percent of the time.

These statistical analyses show that for one set of random samples (one bottle) at the four sampling stations, the maximum deviation from the average concentration may vary as much as ±25 percent. For two consecutive sets of samples, the maximum deviation from the mean may be as much as ±19 percent. In the routine collection of samples the probable deviation from the mean will vary from zero to these maximum percentages based on this statistical study.

To eliminate in part the possibility of obtaining a sample of high concentration from one of the eddies over the measuring sill, a 3/16-in. sampler nozzle was used. This permitted a slower filling rate, and the sample was obtained over a longer period of time than with the 1/4-in. nozzle. The relatively longer sampling "thread" tended to average out intermittent periods of high and low concentration.

A study of all samples collected during the period July 15, 1949, to November 30, 1950, indicated that the concentration of suspended sediment at any one sampling vertical on the measuring sill varied considerably from the mean and that some of the verticals in the cross section were subject to wider variations than others. Therefore, a study was made to determine which combination of sampling verticals would define the representative concentration of the cross section.

Twenty suspended-sediment discharge measurements collected at the measuring sill of the turbulence flume were analyzed to determine the proper sampling verticals that would define the true concentration of the cross section. Several combinations of verticals were inspected to find the combination that would best define the concentration of flow. It was found that stations 10, 30, 50, and 70, which were being used as the daily sampling verticals at the time of this special study, provided the most desirable results. The average ratio of the concentration in the cross section to the concentration at the daily stations for the 20 samples analyzed was 1.0002, and the maximum deviation of the 20 measurements was 28 percent. Such results are considered satisfactory.

Figure 23 shows typical lateral distributions of velocity, concentration, and size of suspended sediment at the measuring sill. Samples collected at 1-ft intervals at the measuring sill did not indicate any pattern of concentration downstream from each row of 1- by 2-ft baffles.

Dune Action Upstream From and Through the Flume

The material comprising the bed load is transported in the form of dunes of irregular size and shape. The bed load does not move in the form of dunes for all cross sections, as many of the wider sections of the Loup River will transport their bed load in sheet movement. Field data were collected in the reach directly upstream from the turbulence flume to determine something of the nature of the movement of bed-load material, as to both quantity and rate, and of the changes in configuration of the bed.

A grid system was laid out in the reach directly upstream from the flume by stringing ropes at 5-ft intervals from the catwalk at the measuring sill to a tagline spanning the river about 90 ft upstream. Flags were tied to the longitudinal ropes at increments of 5 ft. The data were then collected by reading the elevation of the stream bed with levels and by noting the depth of flow directly from the level rod. Care was taken to disturb the bed as little as possible, but the dunes were found to re-form almost immediately when disturbed. By collecting a complete set of soundings in the reach at intervals of 1 hr, it was possible to chart the average rate, direction, and quantity of movement of some of the major dunes that retained their same approximate dimensions as they approached the turbulence flume. Soundings were taken in the upstream end of the flume to determine the configurations of the stream bed as the initial turbulence induced by the flume began to suspend the bed-load material.

Figures 24 and 25 show the configuration of the dunes over the entire bed and also are an indication of the amount and direction of movement of dunes over a period of approximately 1 hr. Contour lines were plotted directly from level notes, and thus maximum readings represent minimum stream-bed elevations. Computations from these data indicated that the height of the sand dunes varied from approximately 0.2 to 1.6 ft, and the average was approximately 0.7 ft.

The velocity of movement of the dunes was considered to be the average of the velocity of the crest and the velocity of the trough. An entire trough-crest combination was studied over a period of time, and the average velocity of the crest and trough was determined. The velocity of the crest varied from 1.2 to 15.6 ft per hr, and the velocity of the trough varied from 4.1 to 13.0 ft per hr. The average velocity of the dune was approximately 7.3 ft per hr. These measurements are of necessity only approximate, but they do give an indication of the order of magnitude of the velocity of the dune movement in this particular river. By assuming that the average height of the dunes was 0.7 ft and that the average velocity of movement of the dunes was 7.3 ft per hr, the concentration of sediment that moved as dunes was approximately equivalent to 310 ppm.

In walking over the bed of the river, it was noticeable that certain areas of the dunes were stable and other areas of the dunes were fluid. Those that were the most fluid were forming and moving most rapidly. Although the predominant direction of movement of the dunes was parallel to the direction of flow, many of the dunes had a tendency to move diagonally to the left or to the right.

The crest of the large dunes when approaching the flume would at times be at an elevation higher than the top of the baffle plates in the flume. As these dunes moved toward the upstream baffle plate, it appeared as though the baffle would be covered. However, when each dune reached a point within about 1 ft of the baffle plate, the downstream side of the dune would begin to

be carried into suspension; in this manner, most of the dunes were prevented from covering the baffles. Occasionally, however, the dunes were sufficiently large to cover the upstream baffle and move on to the second baffle. In moving from the upstream baffle to the second baffle, a higher percentage of such a dune would be carried into suspension so that the dune was never able to cover completely any of the baffles in the second row. As the dune moved on downstream, the upstream baffle would slowly emerge through the top of the dune. The dune would rapidly be forced into suspension by the increased turbulence and would be carried on downstream.

By the time the dunes had traveled past the first four rows of baffles, only a small amount of the material was being transported as bed load along the floor of the flume. Deposits on the downstream side of each of the baffle plates were relatively stable and changed very little in size or shape with time. Samples taken from these deposits on the downstream side of the baffles indicated that the material deposited was coarser for the downstream baffles than it was for the upstream baffles. Coarse material with a maximum diameter of 11/4 in. along the principal axis would occasionally be found on the upstream side of the 6-in. baffle and the measuring sill. Such material was apparently being carried over the measuring sill as bed load. Because the quantity of this material was so extremely small compared with the total load carried over the sill in suspension, it was considered negligible.

Increased Turbulence Through Flume

The quantity of head loss in flow through the flume is a measure of the energy dissipated as turbulence.

The longitudinal length of the flume is 38 ft. For average discharges the fall through the flume was about 0.35 ft. The normal slope of the river reach adjacent to the flume averages 7 ft per mile, or 0.00133 ft per ft. This slope when multiplied by the length of the flume would indicate a normal fall of 0.051 ft. This fall differs by about 0.3 ft from the measured fall of the water surface through the flume and constitutes the amount of head loss that is due to the dissipation of energy by turbulence.

Model-Prototype Comparison

Although it was hoped that an accurate comparison of the behavior of the model and the behavior of the prototype structure could be made, there were several reasons why the model could not be operated under exactly dynamically similar conditions as the prototype. In view of this situation, the data from the model cannot be expected to compare exactly with the data from the prototype.

The model was arranged so that the floor was horizontal, and the upstream reach of the model channel of necessity could not be exactly similar to that of the prototype. Furthermore, a section of the river and structure was taken so that the side effects and the boundary layer developed along the glass wall were different from those found in the prototype. The sand used in the model was somewhat larger than that which would be dynamically similar to the sand in the prototype. Therefore, only an approximate comparison regarding the scour is possible. The exact sediment concentration and water discharge for the prototype could not be anticipated when the initial model studies were made, and therefore the model was tested at approximate concentrations and rates of discharge.

In spite of these differences, several interesting and significant comparisons can be made. The model studies indicated that if all the baffles were at least 1.0 ft high, the measuring sill would be clear. In the prototype, this was found to be true except for the region in which peculiar flow patterns existed and caused deposition. Two of the irregularities were an interference of the flow pattern caused by deposits of debris upstream and downstream from the north section and a slight change in alinement of the river. Because of these peculiar situations in the prototype, it was necessary to increase the height of the two upstream rows of baffles to 1.5 ft. By this means the measuring sill was kept clear throughout its length, and none of the baffles were covered permanently.

Observations of the model indicated that the dunes form a certain pattern as they approach the first baffle. As they pass succeeding baffles, the turbulence created forces the dunes into suspension. Similarly, observations of the prototype showed that the same type of dune pattern was developed and that the dunes moved down among the baffles in approximately the same fashion as in the model. In some parts of the prototype flume the dunes were forced completely into suspension further upstream than in the model, and in other parts of the prototype the dunes were forced completely into suspension further downstream than in the model. These differences can be explained at least in part by the peculiar prototype situation that caused a three dimensional and unsymmetrical flow pattern in the prototype.

The concentration of sediment moving over the measuring sill and the variation of this concentration, both vertically and horizontally in the prototype, are somewhat different from those experienced in the model. In the model, the concentration distribution was rather uniform laterally, and the vertical distribution showed a gradual decrease in concentration with height above the sill. In the prototype, however, this concentration distribution was rather irregular. Again, however, most of these irregularities appear to be associated with the peculiarities of the prototype structure because of the shape and nature of the river channel upstream and downstream from the structure.

The total concentration of sediment carried in suspension upstream from the flume, the concentration carried as bed load in the form of dunes, and the concentration carried in the form of saltation (unmeasured suspended load) and bed load that is not moving as dunes seemed to compare very well with the same concentrations measured in the prototype. In the model, 62 percent of the total concentration was transported as suspended load at an alluvial section, 22 percent was traveling as dunes, and 16 percent was traveling as unmeasured suspended and bed load. In the prototype, the comparable percentages would be 53, 29, and 18, respectively.

The height of the dunes that approached the prototype averaged about 0.7 ft, whereas the model indicated that the height of these dunes would be approximately 0.35 ft. This is a twofold difference in the size of the dunes and may be explained, at least in part, by the fact that the concentration in the prototype was approximately twice that in the model. The velocity of the dunes was approximately 7.2 fps in the prototype, and the model indicated that the velocity of these dunes would be 7.8 fps. This comparison, in view of the approximate nature of the measurements made, is regarded as remarkably similar. It is to be expected, however, that the velocity of the dunes would be approximately the same in the prototype as indicated by the model, as the rate of movement of bed load, and hence the dunes, is proportional to the velocity of the stream.

SUMMARY

This investigation, including both model and prototype studies, indicates that generally it is possible to determine in advance, by means of a model, an approximate quantitative measure of the action of a prototype structure that involves the transportation of sediment. Such a comparison is possible because the turbulence created results in the forces of inertia being predominant over the forces of viscosity in connection with the boundary layer development. The predominance of the forces of inertia over the forces of viscosity reduces or almost eliminates the importance of the Reynolds number, Furthermore, the sediment is characterized by its settling velocity in using dynamically similar material in the model as compared with that in the prototype.

It is interesting to note that where the Reynolds number is involved in the fall velocity of the sediment particles, the influence of viscosity is taken into account and reflected by the fall velocity of the particles. Therefore, Reynolds number and viscosity enter the problem only indirectly.

The information available is not sufficient to determine positively whether the model would be able to give an exact indication of the quantitative action of the prototype if it were geometrically and dynamically similar to the prototype.

The studies of the prototype indicate that the roughness available is sufficient to introduce the turbulence required to transport the total sediment load in suspension for the concentration and flow encountered.

ACKNOWLEDGMENTS

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Acknowledgment is also due to the following: Earle Chamness, David Navon, and Pavel Novak (formerly graduate students at Colorado A & M College) for their assistance in the model studies and analysis of data; R. E. Oltman, Assoc. M. ASCE (USGS) for preparing the construction plans for the prototype flume and supervising a major part of the construction work; and R. B. Vice, Assoc. M. ASCE (USGS) for supervising the completion of the installation and the collection of the basic data.

BIBLIOGRAPHY

1. Albertson, M. L., 1948, Design of the Loup River bed load measurement structure, Special rept. to U. S. Geol. Survey from Civil Eng. Dept., Colorado A & M College, Fort Collins (unpublished).

2. Gilbert, G. K., 1914, Transportation of debris by running water: U. S. Geol. Survey Prof. Paper 86.

3. O'Brien, M. P., 1933, Review of the theory of turbulent flow and its relation to sediment transportation: Am. Geophys. Union Trans.

4. Straub, L. G., 1933, Some observations of sorting of river sediments: Am. Geophys. Union Trans.

5. Kramer, Hans, 1935, Sand mixtures and sand movement in fluvial models: Am. Soc. Civil Eng. Trans., vol. 100.

6. Einstein, H. A., Calibrating the bed-load trap as used in the Rhine: Schweizerische Bauzeitung, vol. 110, no. 14.

7. Vogel, H. D., 1932, Geometric versus hydraulic similitude: Civil Eng., August.

8. Du Boys, P., 1879, Le Rhone et les rivieres a lit affouillable: Annales des ponts et chaussees, ser. 5, vol. 18, pp. 141-195.

9. White, C. M., 1940, Equilibrium of grains on bed of stream: Proc. Royal Soc. (London), vol. 174A, pp. 322-334.

10. Meyer-Peter, E., Favre, H., and Einstein, H. A., 1934, Neure versuchsresultate uber den Geschiebetrieb, Schweizerische Bauzeitung, no. 103.

11. Johnson, J. W., 1944, Rectangular artificial roughness in open channels: Am. Geophys. Union Trans., pt. 6.

12. Powell, R. W., 1946, Flow in a channel of definite roughness: Am. Soc. Civil Eng. Trans., vol. 111.

13. Love, S. K., and Benedict, P. C., 1948, Discharge and sediment loads in the Boise River drainage basin, Idaho, 1939-40: U. S. Geol. Survey Water-Supply Paper 1048.

14. Univ. of Iowa and Univ. of Minnesota, Interagency Rept., A study of methods used in measurement and analysis of sediment loads in streams: Rept. Nos. 1-8, St. Paul Eng. Office, St. Paul, Minn.

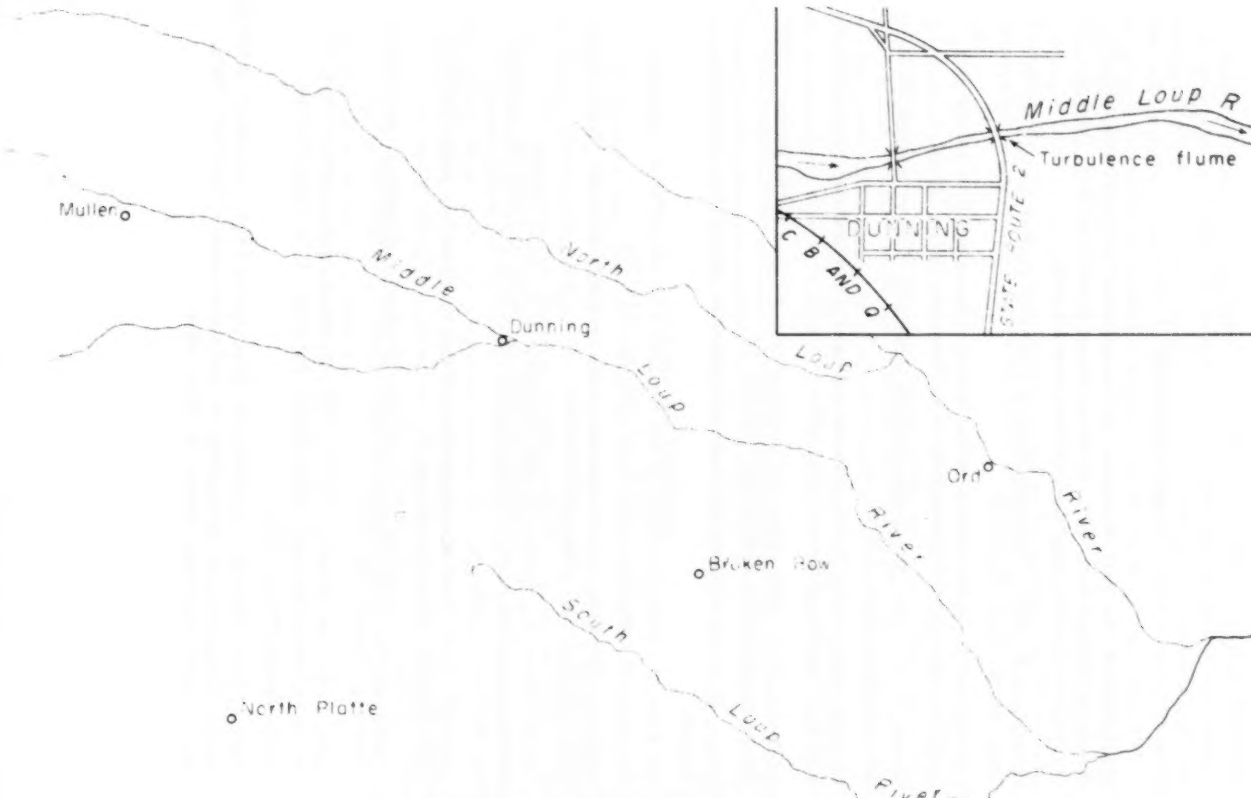


Figure 1.--Loup River Basin, Nebr.

Figure 2.--Looking downstream towards highway bridge, Middle Loup River at Dunning, Nebr.

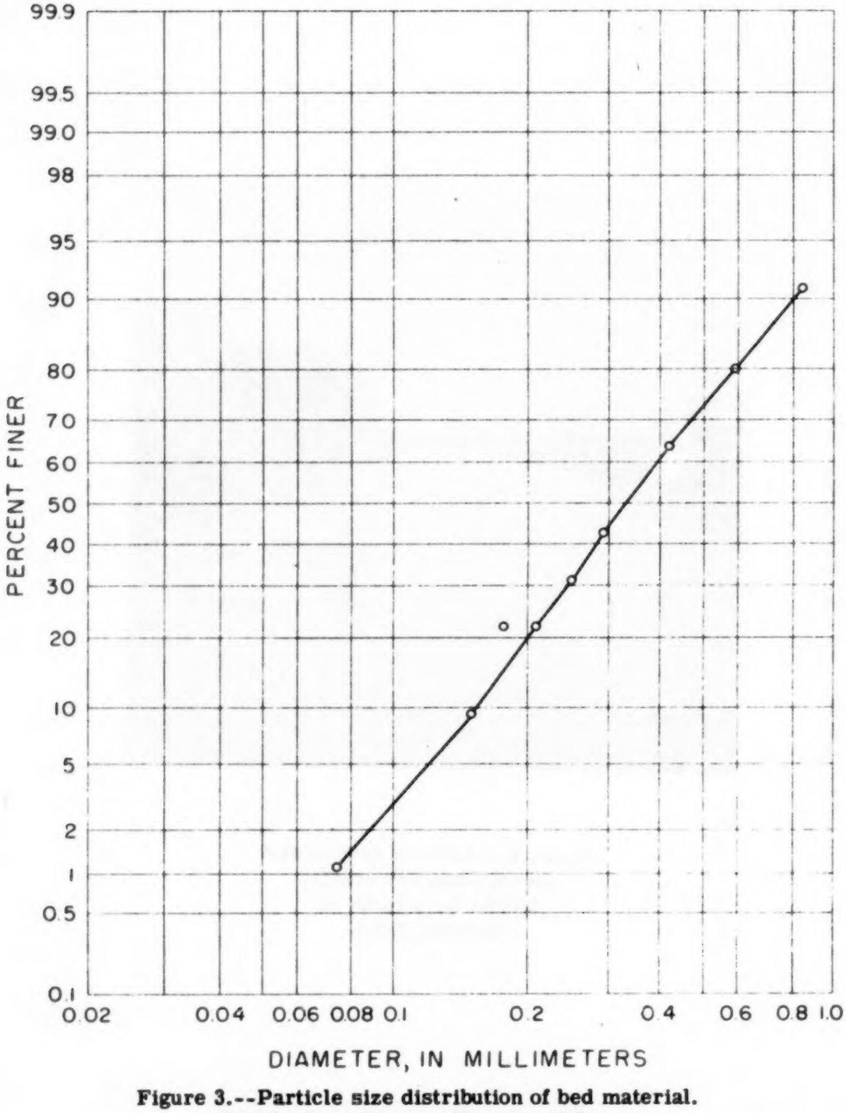


Figure 3.--Particle size distribution of bed material. Middle Loup River at Dunning, Nebr.

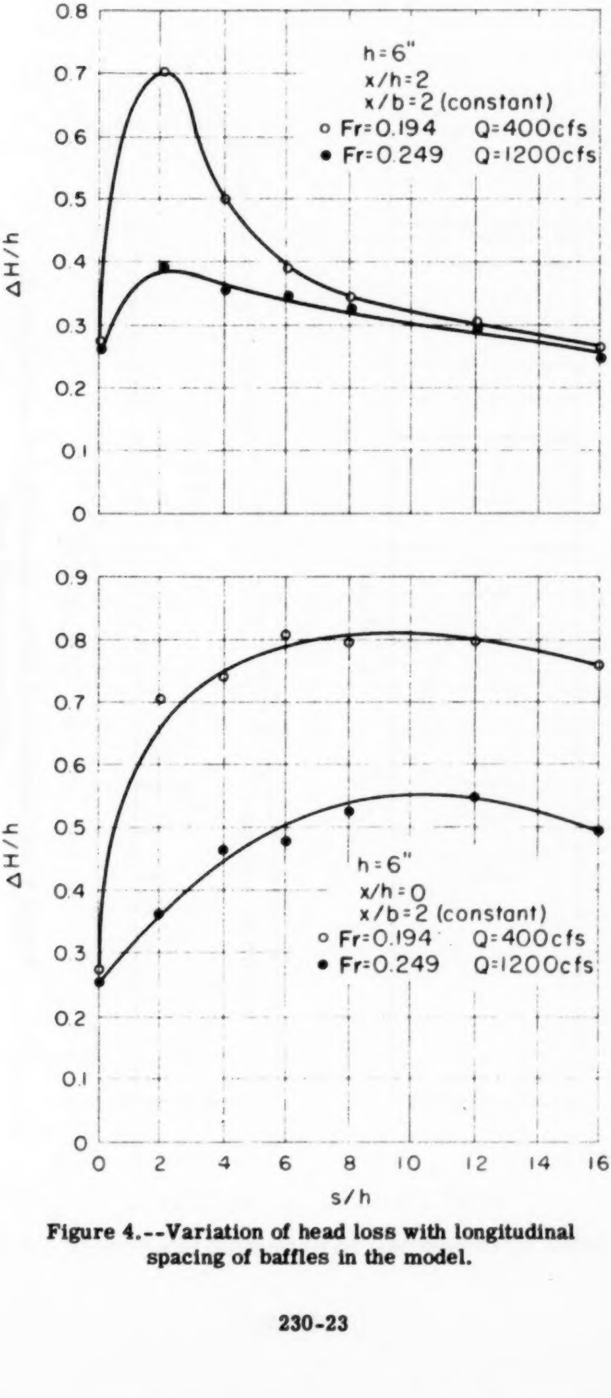


Figure 4.--Variation of head loss with longitudinal spacing of baffles in the model.

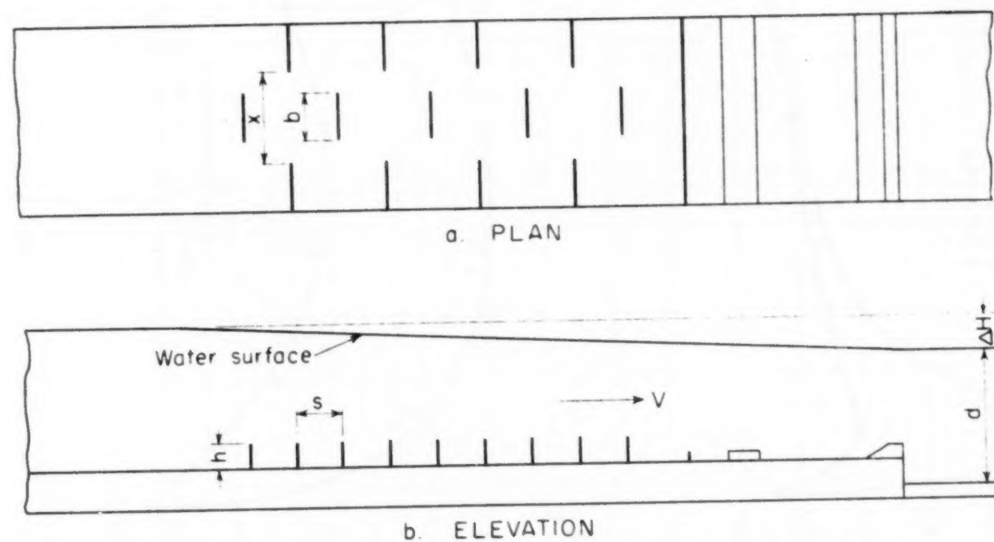


Figure 5.--Arrangement of baffles, measuring sill, and end sill in preliminary model tests.

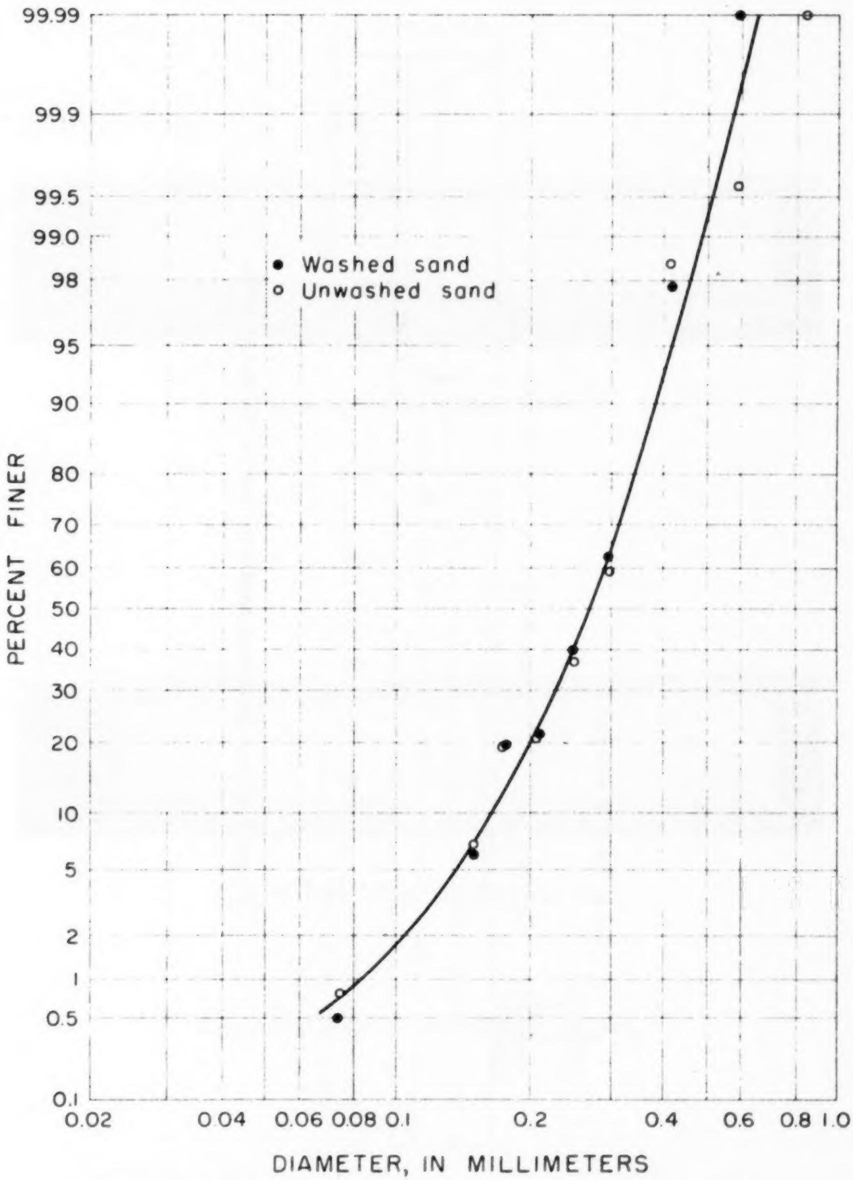


Figure 6.--Particle size distribution of sand used in the model.

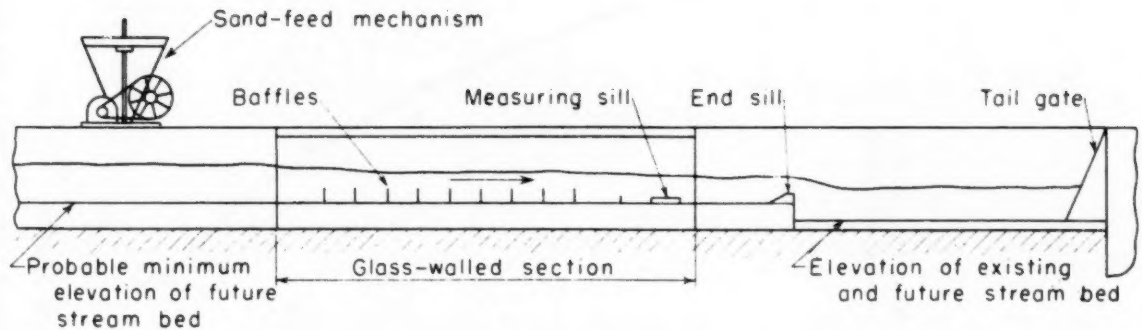


Figure 7.--Arrangement of apparatus used in the model tests.

a. Flume with a discharge of 400 cfs.

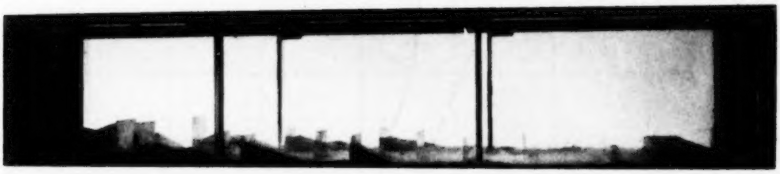
b. Configuration of bed after test run.

Figure 8.--Model flume with 6-in. baffles.

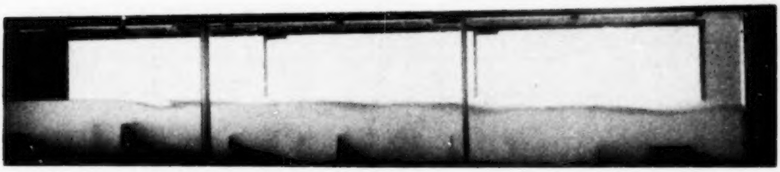
a. Flume with a discharge of 400 cfs.

b. Configuration of bed after test run.

Figure 9.--Model flume with 1-ft baffles.



a. Configuration of bed after test run.



b. Flume with a discharge of 400 cfs.

Figure 10.--Model flume with 1.5-ft and 1.0-ft baffles.

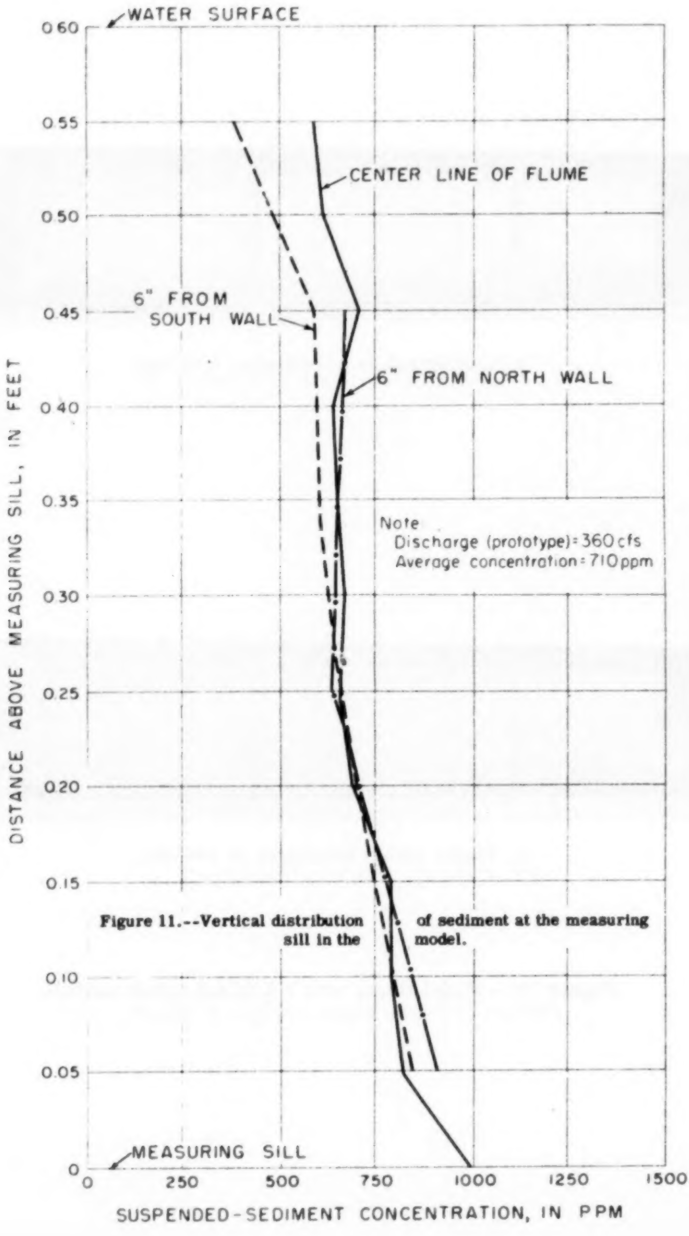


Figure 11.--Vertical distribution of sediment at the measuring sill in the model.

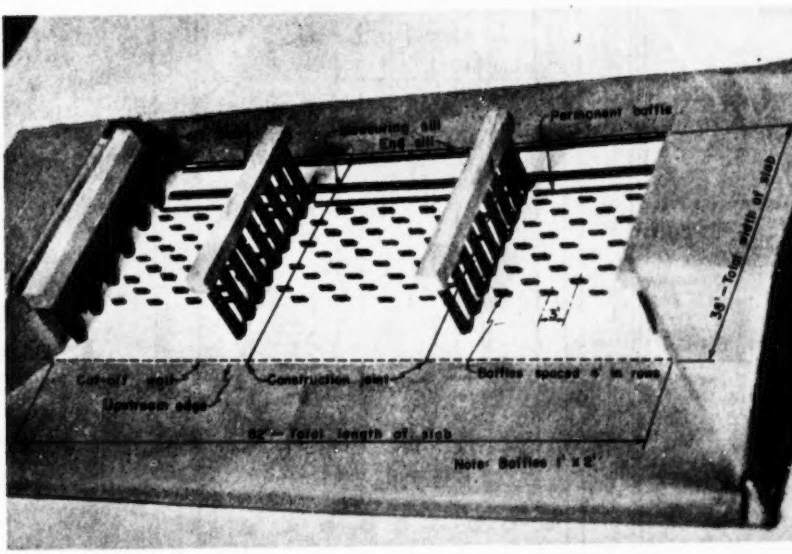


Figure 12.--Skeleton model of prototype flume.

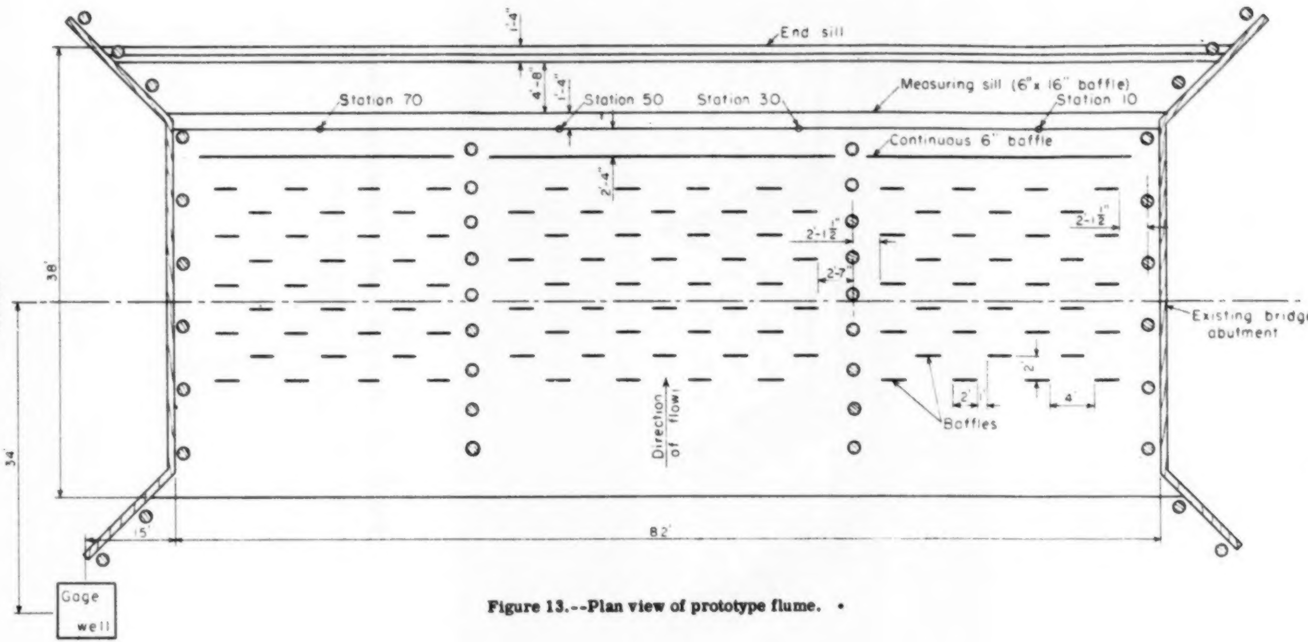


Figure 13.--Plan view of prototype flume.

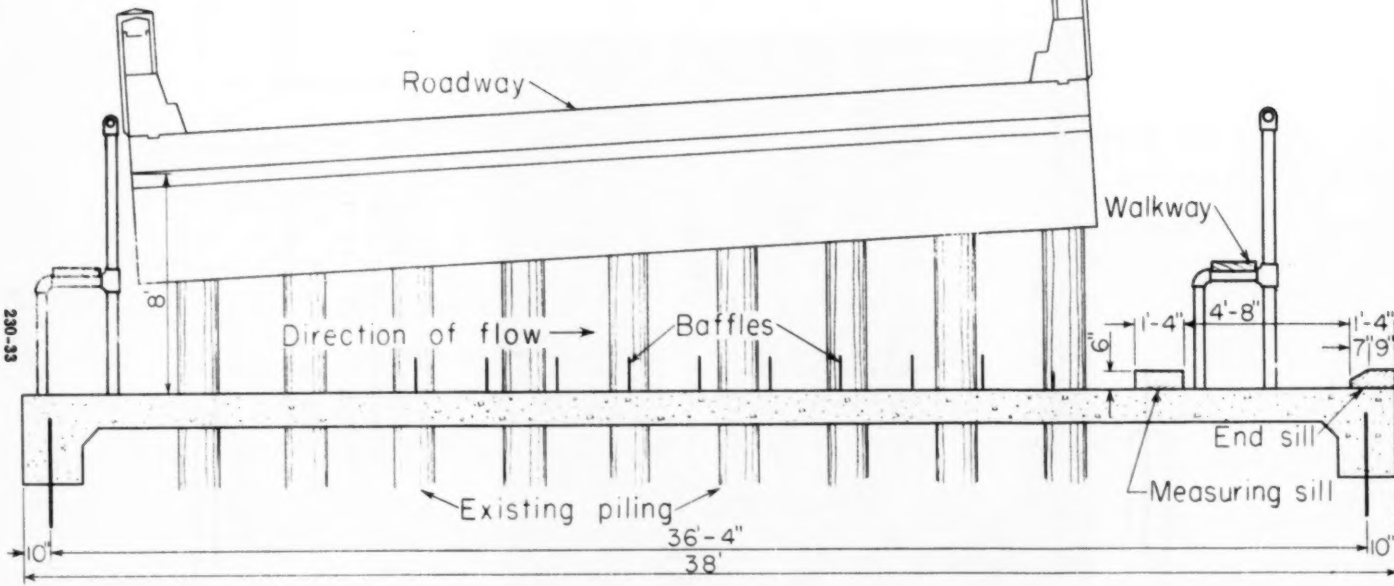
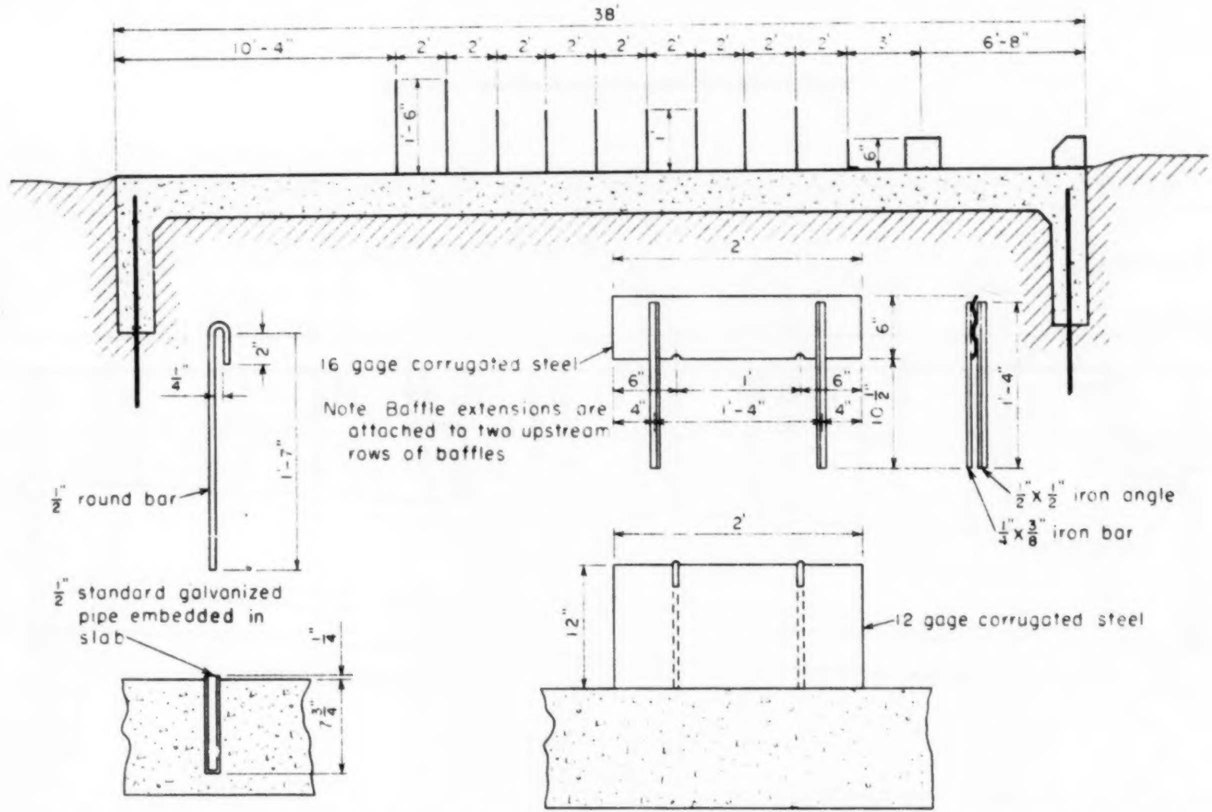


Figure 14.--Section of prototype flume and highway bridge.



HOOK AND SOCKET DETAILS BAFFLE AND BAFFLE PLATE EXTENSION DETAILS **Figure 15.**

Figure 16.--Looking upstream at baffles. Measuring sill (6 by 16 in. wooden baffle) in immediate foreground.

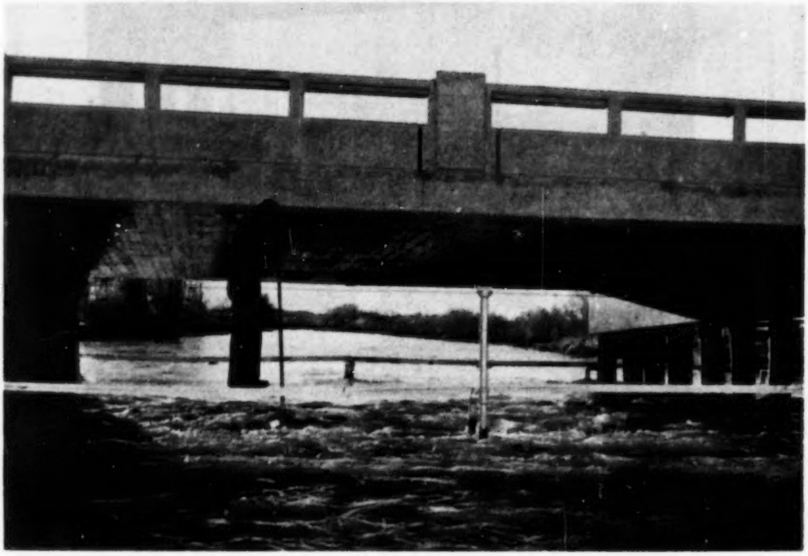


Figure 17.--Looking upstream at the prototype flume at a discharge of 350 cfs.

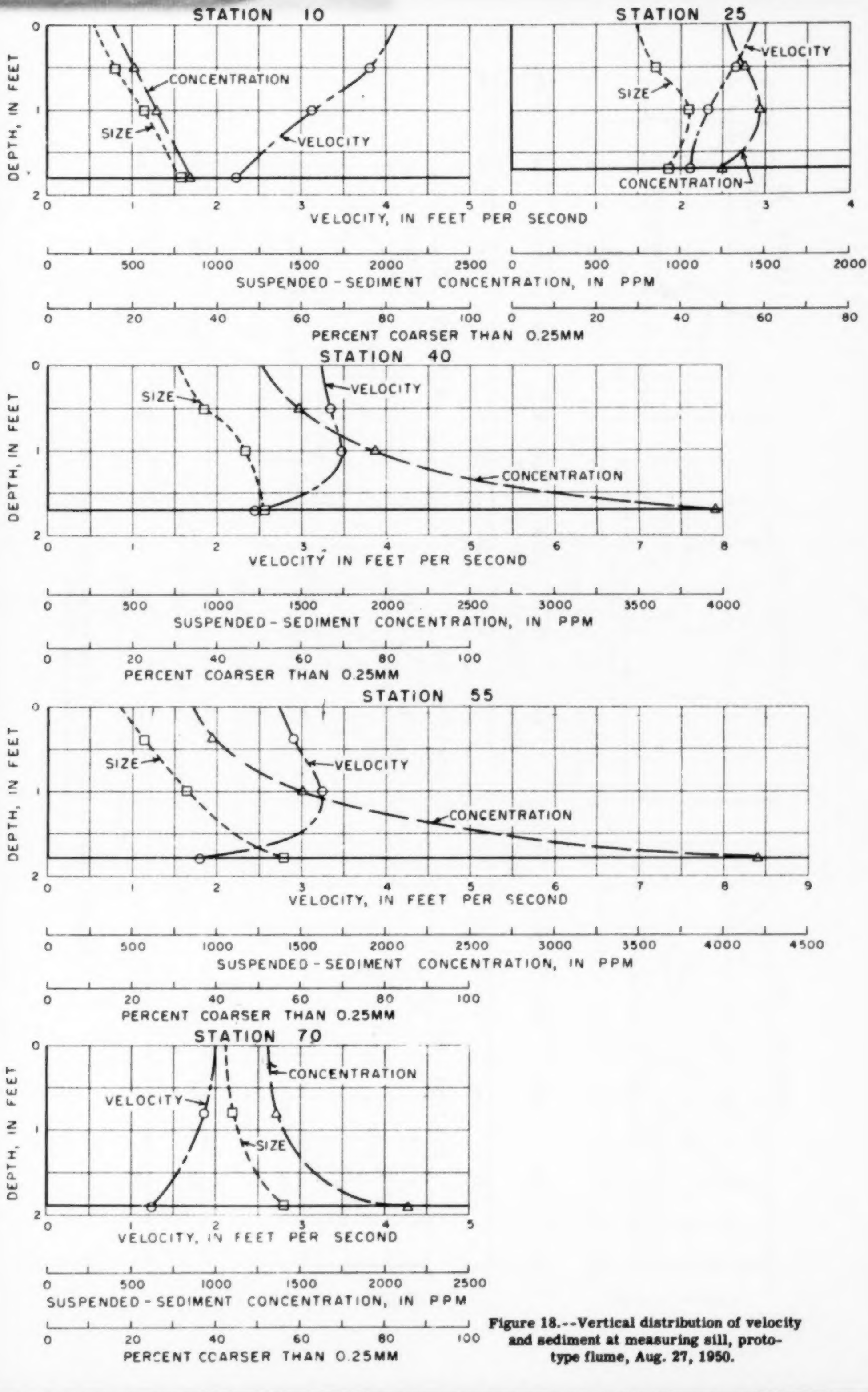


Figure 18.--Vertical distribution of velocity and sediment at measuring sill, prototype flume, Aug. 27, 1950.

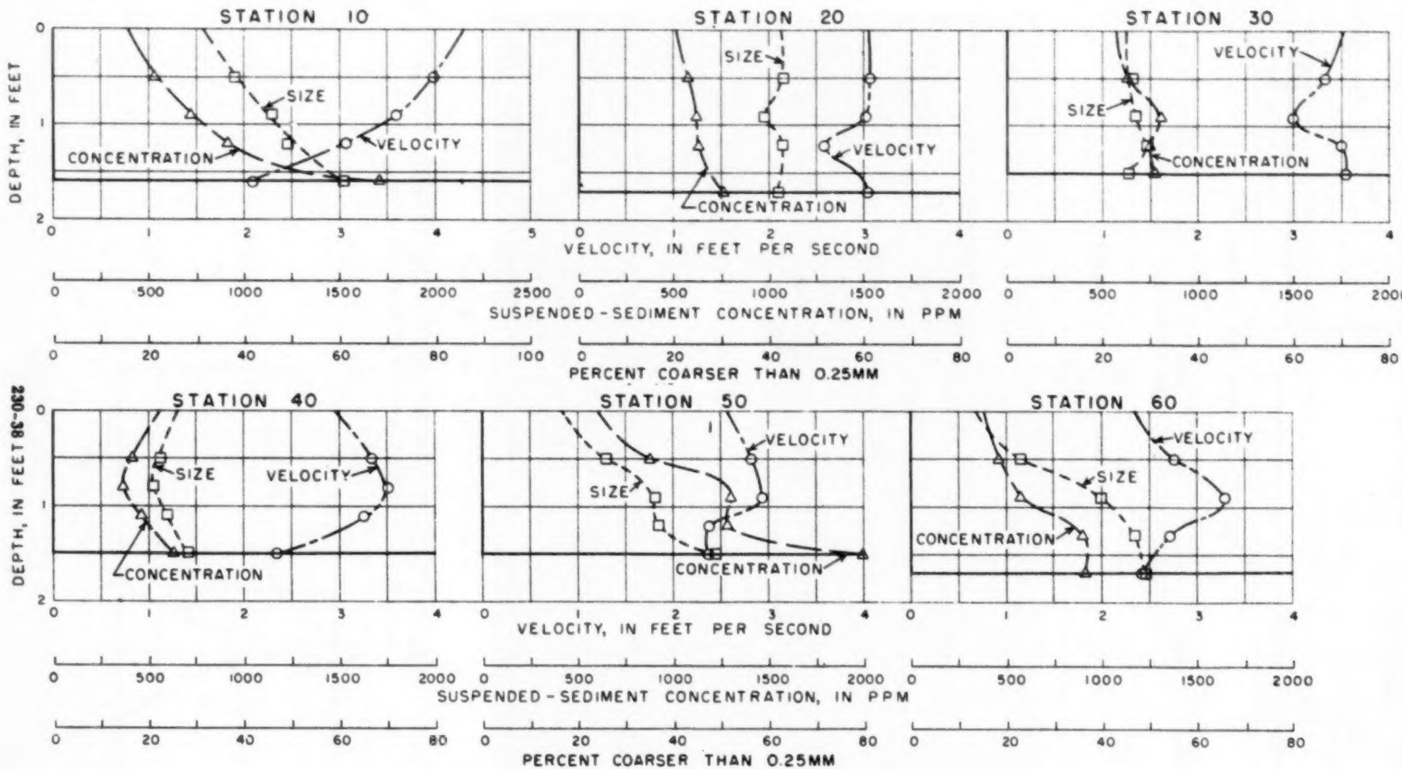


Figure 19.--Vertical distribution of velocity and sediment at measuring sill, prototype flume, Aug. 30, 1951.

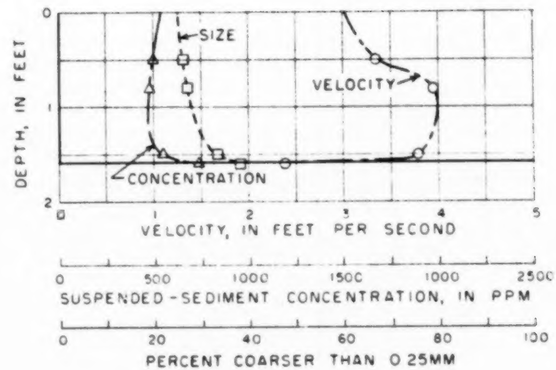
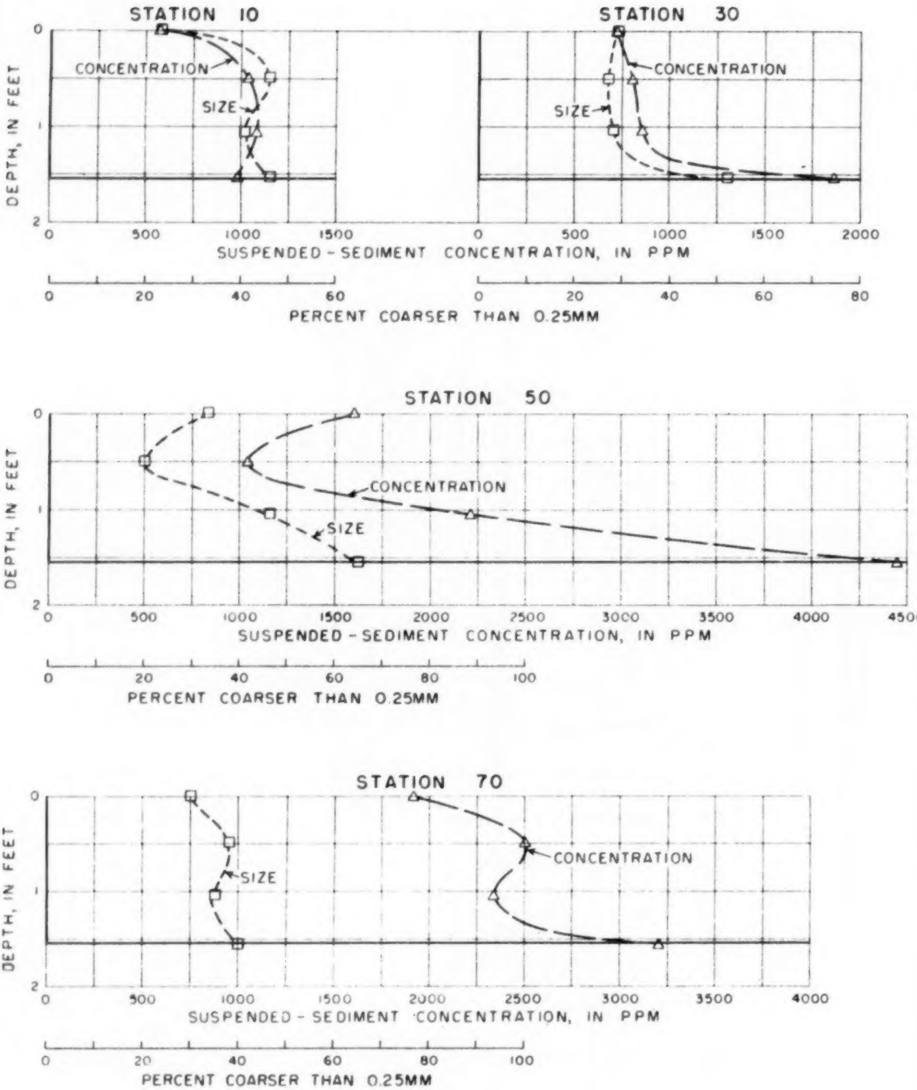


Figure 19.--Station 70.



Note: Samples collected with Tait-Binckley sampler

Figure 20.--Vertical distribution of velocity and sediment at measuring sill, prototype flume, Nov. 29, 1951.

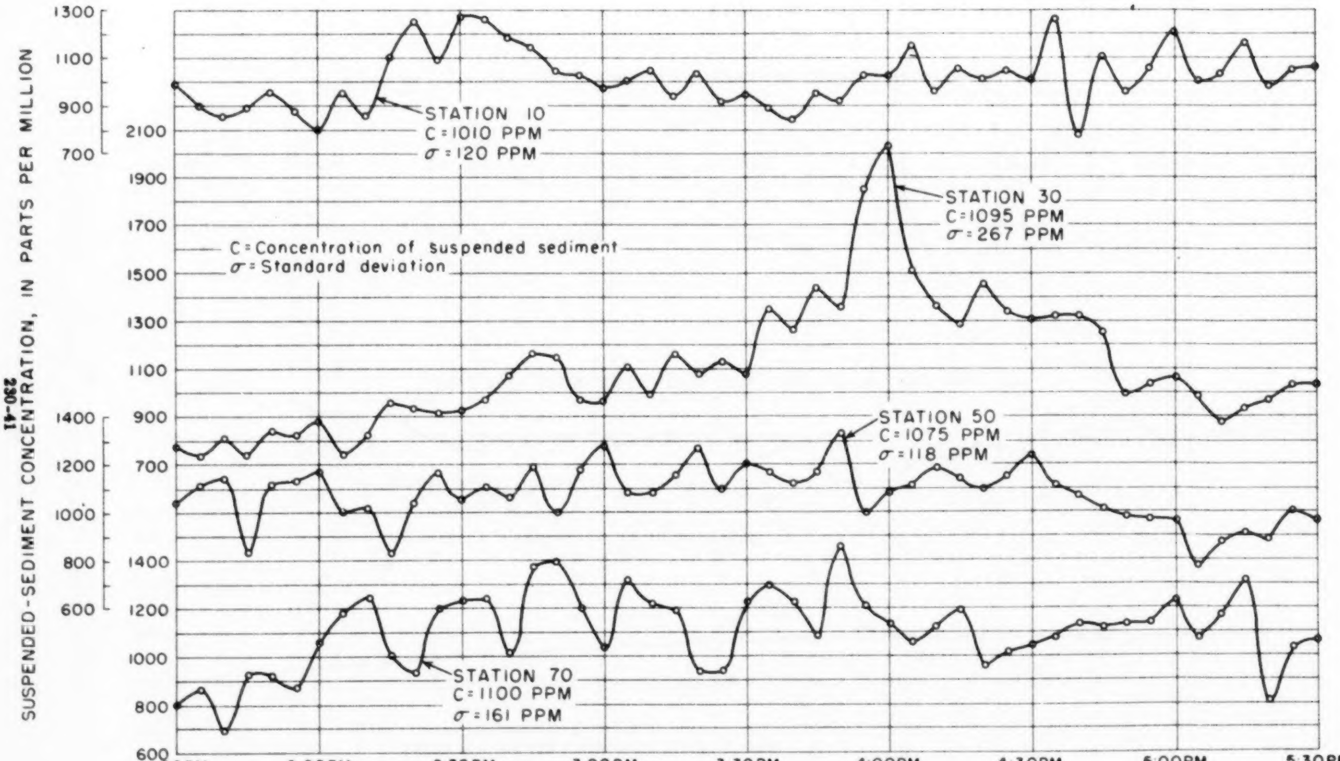


Figure 21.--Variation of sediment concentration, prototype flume, June 27, 1951. Water discharge, 364 cfs.

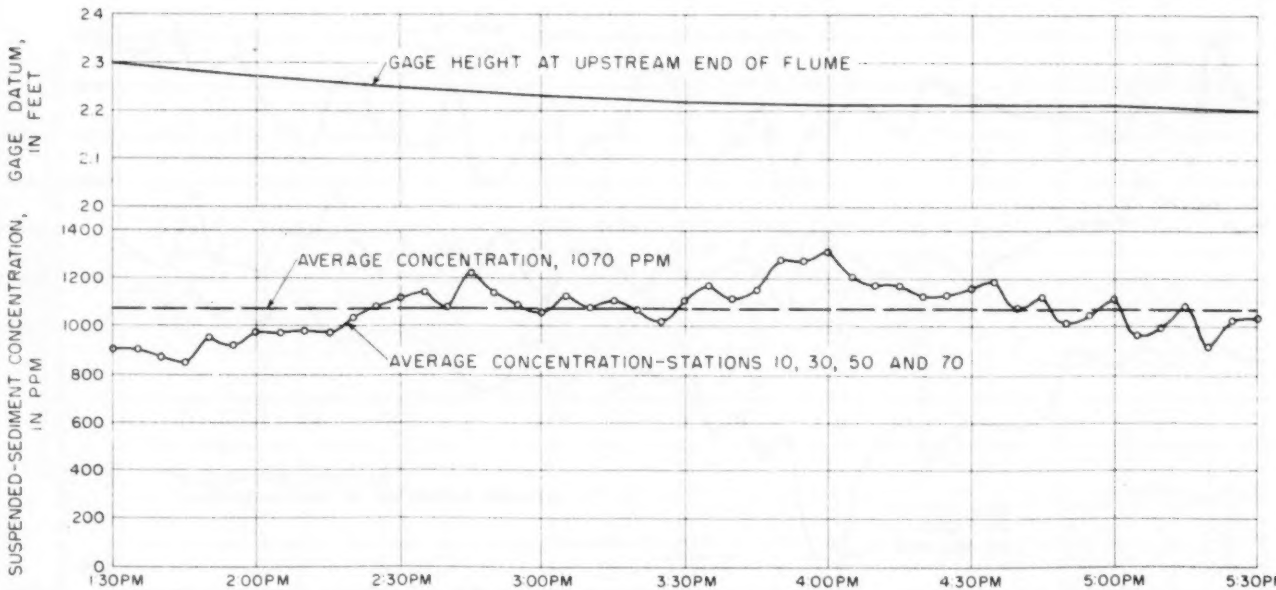


Figure 22.--Average variation of sediment concentration, prototype flume, June 27, 1951.

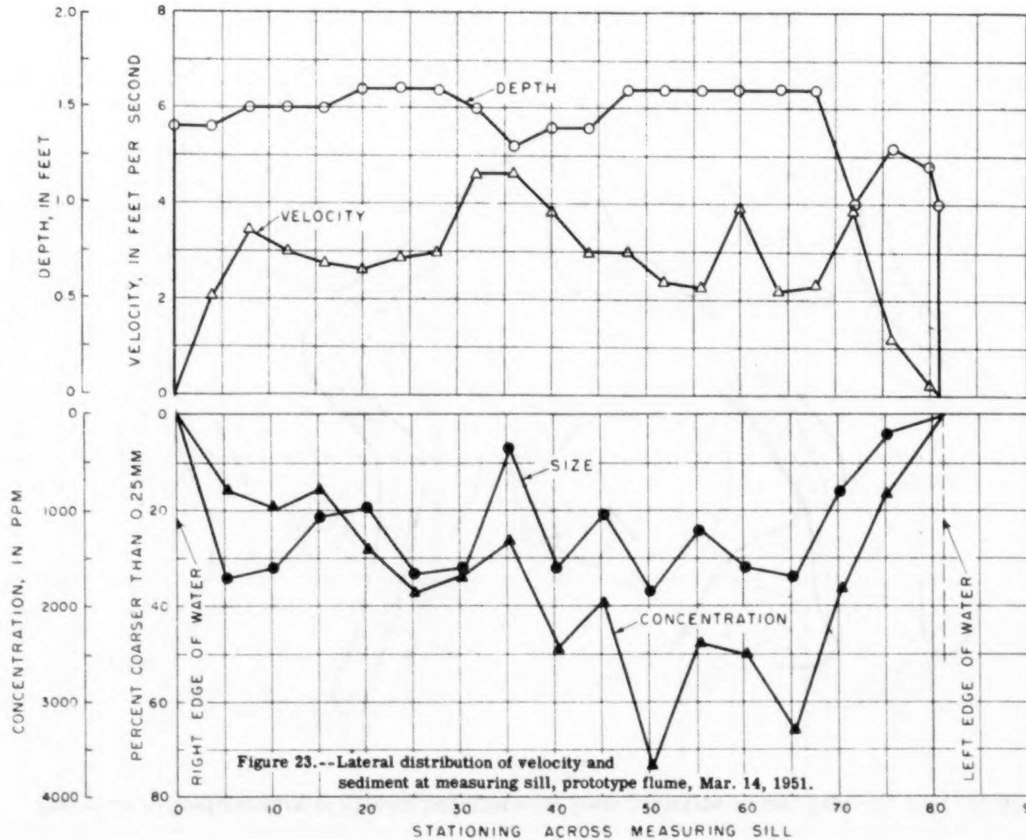
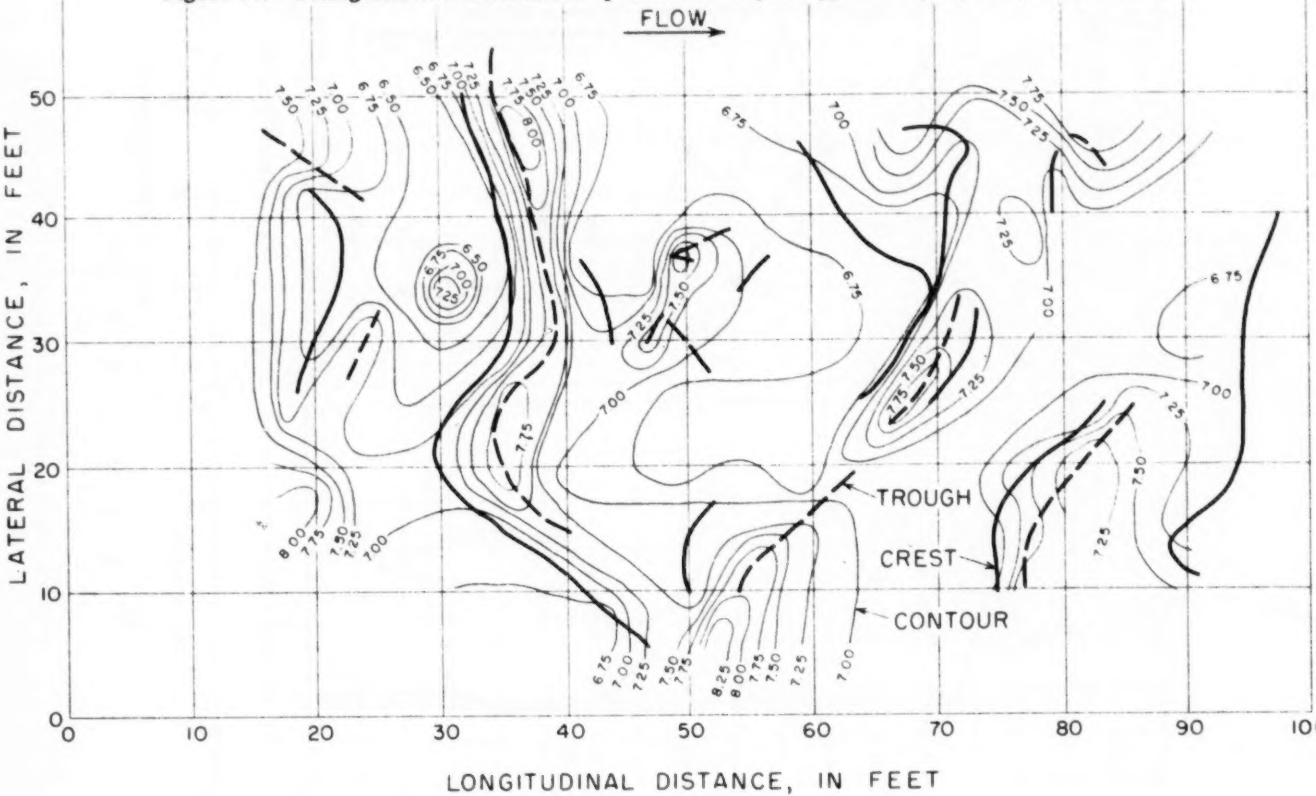


Figure 23.--Lateral distribution of velocity and sediment at measuring sill, prototype flume, Mar. 14, 1951.

Figure 24.--Configuration of stream bed upstream from prototype flume, Sept. 20, 1951, 12:30 p.m.



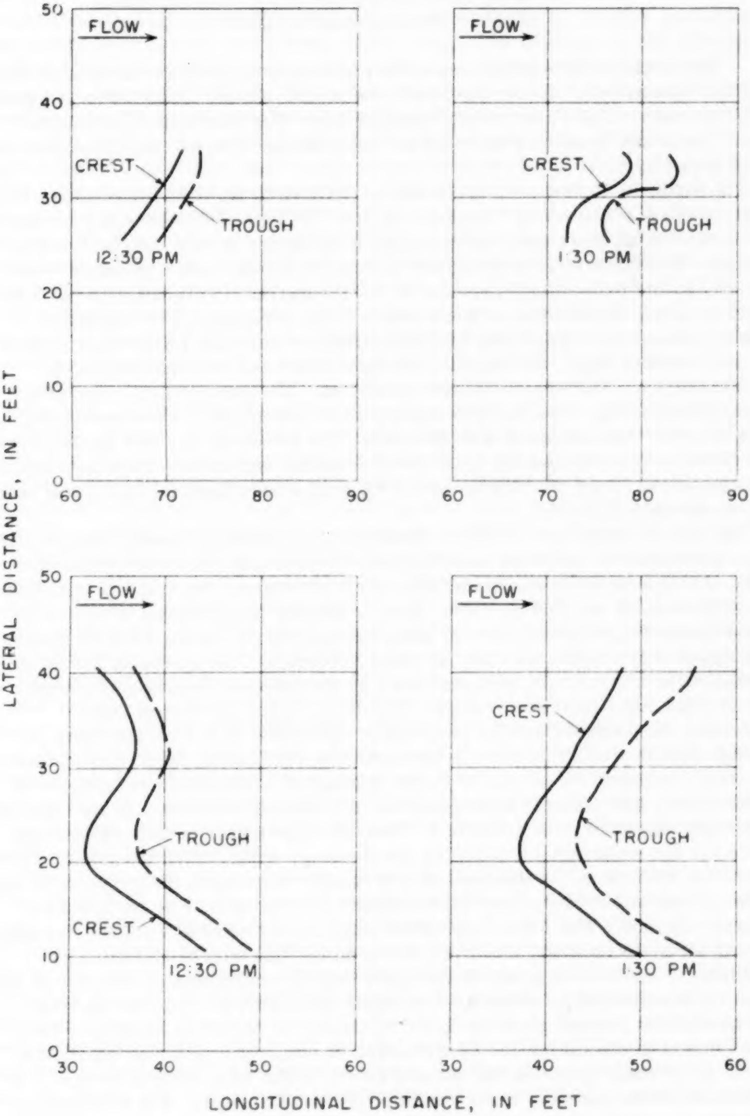


Figure 25.--Typical dune movement upstream from prototype flume for 1-hr period, Sept. 20, 1951.

Discussion

Total Sediment Load Measured by Turbulence Flume
Corbet, Hansen, and Borland

The authors have presented a very interesting paper on the design and also the operation of the turbulence flume on the Middle Loup River at Dunning, Nebraska. The information resulting from the operation of the turbulence flume has been very valuable in the planning of water resource development in the area.

The streams of this area are alluvial and relatively wide and shallow with fairly steep slopes of 6 or 7 feet per mile. The flow of the streams is usually constant with an extremely low probability of having either high or low discharge. The stream flows originate mostly as ground water, seeping either directly to the main-stem streams or to tributaries. Very little of the total drainage area contributes surface runoff to the streams. This condition exists because the topography is Aeolian and because the infiltration rate of the soil is quite high. The surface materials are the residuals from the Aeolian action. The area is known locally as "The Sand Hills," and, geologically speaking, considerable movement is taking place even though the area is fairly well covered with grasses. The sediment carried by the streams, therefore, originates mainly from the streambed and banks. Sand movement and deposition along the stream banks by wind action insures a plentiful supply of sedimentary material.

The use of water from these streams for irrigation purposes requires that some provision be made for handling these sediments. A visual inspection of these streams will show considerable sand movement. Because of the Basin investigations in the Lower Platte River Area for the potential irrigation of approximately 1,700,000 acres of land, the Bureau of Reclamation is vitally interested in the sediment loads of these streams. The necessity for attention to this subject is forcibly demonstrated by the existing sediment disposal pile of the Loup River Power District at their Genoa Diversion Dam.

Anyone responsible for the planning or operation of a diversion dam or storage reservoir in this area is immediately confronted with the problem of the costs that must be allocated to the storage of sediment in reservoirs or in the annual maintenance and operation of sediment handling. In the case of a storage reservoir, the problem is the cost of providing additional storage space for the sediment produced by the drainage area during the contemplated life of the structure. In the case of a diversion structure, the problem is that of the annual cost of handling the sediments by mechanical or by hydraulic disposal method. The water resources plan of development for these steady flowing streams includes more diversion dams than on-channel storage reservoirs, and it is of prime importance that the estimates of the cost of the handling of sediment be consistent with the estimates of costs of the other features of the project planning in determining the potential benefits. This requirement necessitated the construction of some type of field installation which would make possible the measurement of the total sediment load at a particular point, and also make possible the establishment of a correlation with other sampling sites where the total sediment load cannot be developed from a study of the data provided by the standard sampling procedures.

It was observed that a considerable amount of the material appeared to move very close to the bed of the stream, which brought up the question as to the validity of the ordinary sediment sampling methods for determining the

total sediment load. The Dunning turbulence flume was a joint conception of everyone interested in sediment in this area and was primarily developed to evaluate the effectiveness of the ordinary sampling procedures. It was expected that the experience gained from the flume could be used in evaluating the sampling on the other streams in the area. The problem of the adequacy of the ordinary sampling procedures can be further illustrated by a comparison of the sediment transport characteristics of these streams and the results provided by the present sampling procedures and equipment. A typical cross section of a sandhill stream is shallow and wide. For example, eight observations which were made at one section on the Middle Loup River at Dunning for an average discharge of 362 cfs had an average depth of 1.1 foot and an average width of 153 feet. The average velocity was 2.14 feet per second. While the average depth is 1.1 foot, the extremes vary between a few tenths and slightly more than 2.0 feet. The sediment sampling equipment now in use at most stations includes the U.S.DH-48 and the U.S.D-49. Both of these samplers are of the depth-intergrating type. The DH-48 is adapted for use by wading, and the D-49 is adapted for cable suspension use. The intake nozzle for these samplers, of necessity due to construction and operation, is located so that a sample may only be integrated to within 0.4 foot of the stream bed. Therefore, if a stream is wide and shallow, a considerable part of even the normal suspended load may be missed by such a sampler. Figure 1 shows a typical vertical sediment distribution curve obtained on a sandhill-type stream. Also shown in this illustration is a sketch of a D-49 sampler showing the location of the nozzle with respect to its lowest extremity. The vertical sediment distribution curve was obtained for a vertical having a depth of 2.3 feet as may be noted by the vertical ordinate. The sampler, therefore, will only obtain a sample to a depth, in this case, of 1.9 foot. The sampler will integrate with respect to depth and velocity that portion of the curve designated as A. The common method of converting the concentration represented by the integrated portion "A" to sediment movement in tons is by multiplying the concentration by the water discharge. The water discharge is that volume of water moving in the total section which includes that area represented by B. The establishment of a true suspended sediment concentration figure would require an integration of the total vertical including both areas A and B. The magnitude of the error depends upon the depth of the section and the shape of the vertical distribution curve. The characteristics of the sandhill streams are such that both the depth and vertical distribution tend to give a sizeable error.

The intensive sampling studies conducted at Dunning and at other locations in the Sand Hills area has brought out the importance of good sampling technique. When the shape of the vertical sediment distribution curve is such that the concentrations become greater as stream bed is approached, the magnitude of the error increases. It becomes imperative, then, that each sampling station be intensively studied to determine the probable accuracy of the sampling results. This opinion is further borne out by the fact that the percentage of unmeasured sediment varied from about 20 to 60 percent for the different experimental sections which were located above and below the Dunning flume and which were taken by the use of standard procedures and equipment.

One point which the authors failed to emphasize is that the limited size of the material available for suspension makes it possible to sample total load at the turbulence flume. In the conception of the turbulence flume, the following important factors were considered:

1. The material size was limited to that which could be accommodated by the range of nozzle sizes available for use in the standard samplers.

2. The kinetic energy which was developed or produced by the stream was sufficient to place in suspension at the flume the maximum size of sedimentary material contributed by the drainage area or stream bed.

The material from the drainage area is predominately sand, the major portion falling in the fine sand bracket. A size analysis of the bed material of the Middle Loup River near Dunning shows that approximately 90 percent is finer than one millimeter, and about 98 percent is finer than four millimeters. This analysis really defines a material that is coarser than the average of the bed materials from which it originates since a sorting action has taken place, causing the coarser material to be residual on the stream bed.

The authors refer in their paper to the altered vertical distribution of the sediment load which results from the induced turbulence created by the baffle plates of the flume placing in suspension all of the sediment carried by the stream. This condition is generally true as was noted in the operation of the flume. However, it has been noted on several occasions that the vertical distribution of the sediments, particularly in the coarser sand factions, increases measurably toward the bottom of the vertical section. The use of the sill downstream from the baffle plates makes it possible to place the sampling nozzle directly on the lip of the sill and thereby sample the entire vertical sediment load. To insure that this is done for each sample, a set of guides has been constructed whereby the sampler is guided in its vertical movement. Careless or indiscriminate sampling techniques, even in conjunction with the flume, still would not measure total load at times.

As pointed out by the authors in their paper, the turbulence flume as tested in the laboratory, and as built and operated in the field, is capable of suspending the total sediment load so that it can be measured with existing sampling equipment. However, there is still a need for further study of the hydraulic characteristics of the channel transporting the load, such as the depth, velocity, roughness, and slope, to arrive at a relationship which may be applied to standard measurements to develop total load estimates so that engineers can make more accurate estimates of sediment figures at other sites.

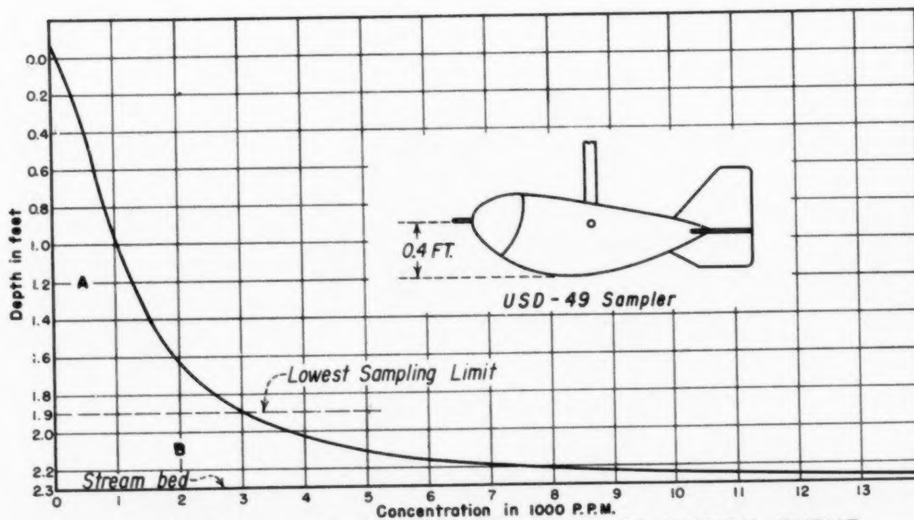


FIGURE I. VERTICAL SEDIMENT DISTRIBUTION CURVE